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100 % RENEWABLES

ENERGY SYSTEM MODELING RESULTS FOR AVELLANEDA, ARGENTINA

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CHP	Combined heat and power plant
PV	Photovoltaic
RE	Renewable energies
GIS	Geoinformation system
BAU	Business-as-usual
GDP	Gross domestic product

Preface to the energy modeling of the City of Avellaneda

On behalf of the Government and the community of Avellaneda we would like to express our gratitude to the Fraunhofer-Institute for Solar Energy Systems, ISE and ICLEI - Local Governments for Sustainability for the report of the Energy Modeling of the city. This document is a valuable input for the planning of the Energy Transition Roadmap and for basing future policies to accompany the energy transition and the ambitions of the Paris Agreement.

The Energy Modeling deepens the description of an energy scenario chosen by the city that will allow it to be 100 % renewable energy by 2050. The city of Avellaneda is rich in renewable energy resources and it is a challenge to use them in a sustainable way. The renewable energy potential has been calculated from a Georeferenced Data System (GIS), statistics and other sources. The chosen scenario contemplates covering 61 % of the demand with photovoltaic solar energy, 20 % with wind energy and the remaining 21 % with biogas generated from waste. This 100 % renewable energy scenario is 54 % more economical and 3.5 times lower in carbon emissions compared to the baseline scenario of using fossil fuels. With the support of international cooperation important progress has been made in strengthening our sustainability agenda.

Having these development opportunities is critical for making the energy transition and climate action a reality for local governments and we are deeply grateful for this.

Gonzalo Braidot
Mayor of Avellaneda

Foreword from the Executive Director of ICLEI – Local Governments for Sustainability Argentina Office

ICLEI – Local Governments for Sustainability is dedicated to support Argentina's efforts in the commitment to increase its clean energy share and to reduce greenhouse gas emissions. Argentina has affirmed its involvement in the Paris agreement, in the Nationally Determined Contribution (NDC), with the energy transition plan to 2030, where the commitment reaches a renewable share of 70 % of the electricity generation installed. Argentina, through the National Climate Change Board, is working on the construction of long-term strategies, with the aim to reach a carbon neutral development by 2050.

To contribute to the global energy transition, ICLEI launched the 100 % Renewable Energy Cities and Regions Roadmap Project, funded by the German International Climate Initiative (IKI). Three cities of Argentina, departments and key ministries of the National Government have partnered with ICLEI and committed to implement this initiative in Argentina, with Avellaneda as the deep-dive city. With our extensive support, ICLEI has collaborated with Fraunhofer ISE to develop the Avellaneda energy modeling to reach the goal of 100 % renewable energy share in all sectors by 2050.

The modeling report constitutes itself as an input for building evidence-based public policies on energy supply, both local, provincial and national. In this regard, it is essential to integrate the characteristics of distribution at the federal level. The modeling report of Avellaneda presents scenarios where energy is provided by local renewable sources to cover the projected demand. The 100 % RE share supply can be achieved by 2050 through solar photovoltaic, biogas and wind power. This document is a key reference for the Roadmap development, and a guide for local action strategies in addressing climate change.

ICLEI Argentina acknowledges the governments of Avellaneda, Rosario and La Plata cities for their commitment and support. Such a milestone would be impossible without the participation of community groups, universities, institutions and many more collaborators. In closing, we would like to express our appreciation to the 100 % renewable energy representatives from ICLEI South America Regional Office, Fraunhofer ISE, and ICLEI World Secretariat for their cooperation.

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1 Summary

Achieving the Paris Agreement on climate change and targets of net-zero emissions in the second half of this century will require an unprecedented transformation of energy supply toward renewables in all sectors and all countries. In the project of 100 % Renewables Cities and Regions Roadmap (100 %RE) project, a total of nine cities and regions from three different countries around the world were selected to develop a plan to achieve an energy system based on 100 percent renewables by 2050. These ambitious energy scenarios shall serve as examples for other cities, provinces, or federal states to show how 100 percent renewable energies are possible in different parts of the world. Therefore, the countries span three different continents and have different boundary conditions for the implementation of renewable energies: Argentina in South America, Kenya in Africa, and Indonesia in Asia. This study covers one part of the project for one of the case studies: the development of 100 percent renewable energy scenarios for the target year 2050 for Avellaneda in Argentina. Avellaneda is a city with 30.000 inhabitants that is located 630 km direct distance north of the capital Buenos Aires. The results of the scenario calculations are then used to develop further action plans and identify projects for the deployment of renewable energy transition.

In order to develop 100 percent renewable energy (RE) scenarios, an energy system model is used (KomMod by Fraunhofer ISE). The deployment of fluctuating renewables and thus of storage technologies, the increase of sector coupling and restricted RE potentials, to name just a few, require the use of computer-aided modeling in order to obtain robust results. The modeling is performed in hourly timesteps to ensure supply security and includes all relevant demand sectors. In the specific case of Avellaneda this is electricity demand, energy for cooking demand in households and commercial sector, heating demand in the commercial and industrial sector, and energy demand for transport on land. All relevant demands are evaluated for today and projected to the year 2050 in different demand scenarios. RE potentials are calculated based on GIS data, statistics data, and studies for Avellaneda, as well as the whole of Argentina when no specific data for Avellaneda is available.

As livestock farming is one of the most important business areas, Avellaneda has a high potential for biogas or biomethane from manure which can be used as fuel to supply electricity as well as heat. Other important renewable energy resources are photovoltaics and wind power.

Six (6) different 100 % RE scenarios are calculated by varying three different features: biomethane fuel price, energy demand and a fixed share of total electricity supplied by wind power plants. In addition, a business-as-usual (BAU) scenario is modelled to allow the comparison of costs and carbon dioxide emissions. This scenario represents a possible national energy system in the year 2050.

A leading scenario has been chosen in workshops between ICLEI, Fraunhofer ISE, and local stakeholders. This scenario uses low fuel price, mean demand and a fixed wind power share of 20 % on electricity supply. In this scenario photovoltaic is the main electricity supplier with a share of 61 %, and biomethane CHPs cover 19 % of the demand. In the least-costs scenario, wind power share is higher with 40 % and photovoltaics cover 42 % while the share of biomethane CHPs stays nearly the same. Heating demand is covered with heat from biomethane CHPs by 49 %, other heat supply technologies are heat pumps and boilers. Energy demand for cooking is mainly covered with gas stoves using biomethane, while electric stoves have only a minor share.

As RE resources, especially for biomethane, free field photovoltaics and wind power, are much higher than demand, the decision of which technologies to use in the future can be based on additional criteria apart from costs and potentials, like acceptance and national and local policies. In addition, a comparison between the 100 % RE scenarios and the business-as-usual scenario shows that all 100 % RE scenarios are cheaper and emit less carbon dioxide emissions than the business-as-usual scenario.

2 The 100 % RE project and its case studies

In order to achieve the Paris climate protection target of net-zero emissions in the second half of this century, an unprecedented transformation of the energy supply toward renewable energies in all sectors is required.
Global electricity demand is projected to increase by 69 % by 2040 (Doman et al. 2016). This will exacerbate the challenge of meeting demand solely from renewable energy sources. In the twenty years from 1990 to 2010, electricity generation from coal decreased by only 3.5 %. Improvements in renewables and energy efficiency were largely offset by higher coal consumption in developing countries (REN21 2014). In other sectors, barriers were even higher: in 2015, renewable energy (RE) contributed to only 4 % of energy consumption in the transportation sector and 8 % in the heating and cooling sector.
The distortion of the energy market by fossil fuel subsidies is a major barrier to the wide-spread adoption of RE. Figures from the International Monetary Fund (IMF) from 2015 show that Argentina, for example, subsidizes fossil fuels to the tune of US$ 206.64 per capita, Indonesia to the tune of US$ 37.65, and Kenya to the tune of US$ 3.67 (Coady et al. 2015). In addition, fossil fuel prices do not reflect the health, environmental, and economic costs of using fossil fuels.
The potential of RE has been poorly tapped in the three target countries of this project Indonesia, Argentina, and Kenya; there is a lack of viable projects for the decentralized generation and use of RE (e.g., from wind, hydropower, geothermal, and biomass) (International Energy Agency 2021). Existing national frameworks do not yet sufficiently support local governments in the three target countries to test and demonstrate innovative and decentralized technologies, practices, and policies to increase the share of RE.
For these reasons, this project supports cities and regions in Argentina, Indonesia, and Kenya in developing strategies for 100 percent RE supply, as well as raising awareness and engagement among shareholders. At the same time, it supports the assessment of local RE potential and project designs, as well as the development of eligible projects. To this end, the project provides tools and resources for a RE-based energy supply.
The project promotes dialogue between various government levels, strengthens capacities, and stimulates the development of appropriate frameworks at national, regional, and local levels - with the aim of promoting the local potential for RE and energy efficiency. As an example, the project aims to demonstrate how local frameworks and projects contribute to achieving national contributions to the NDCs (Nationally Deter-mined Contributions (United Nations Framework Convention on Climate Change) and SDGs (Sustainable development goals).
In each country, one project city/region is designated as a lighthouse city/region (deep-dive cities/regions). This city/region will receive extensive support to build knowledge and competencies as well as consulting services to develop and implement its local strategy for 100 percent RE. The other two cities/regions will be involved in the exchange of experience, knowledge building, peer learning, and policy dialogue as so-called network cities/regions with fewer project resources. The deep dive regions/cities (in bold) and the network cities/regions are named in Table 1.

Table 1: Deep dive and network cities and regions in the three countries in the 100 % RE project

Argentina	Indonesia	Kenya
City of Avellaneda	**Province of West Nusa Tenggara**	**Kisumu County**
City of Rosario	City of Mataram	Mombasa County
City of La Plata	Sumbawa Regency	Nakuru County

Fraunhofer ISE's part in the project is to calculate optimized 100 % RE scenarios for all deep dive regions/cities with the energy system model KomMod, including all relevant demand sectors. The target year for the scenarios is 2050, the latest year by which 100 % RE should be achieved. Several possible energy systems are proposed in which renewables cover all relevant local energy demands, demonstrating how an energy supply based solely on renewables could be achieved. Questions that are answered in this report are:

- How might relevant energy demands develop by 2050, and how high is the electricity demand in 2050 compared to other countries? (Chapter 4.1.2)
- How high are the usable potentials for different kinds of renewable energy technologies? (Chapter 4.2)
- What technology mix achieves the least total system costs while at the same time supplying all energy demands with 100 % renewable energies? (Chapter 6.1)
- How are these technologies operated throughout the year? (Chapter 6.1.3)
- How much storage capacity is needed to use fluctuating renewables in the most optimal way? (Chapter 6.1.1)
- How high are the total system costs in different system configurations? (Including a business-as-usual scenario) (Chapter 6.2)
- What are the levelized costs of energy for the different technologies? (Chapter 6.2)
- What is the influence of a changing biomass fuel price on the results? (Chapter 6.1.2)

Based on these scenarios, pathways for the transformation of the energy system, the 100 % RE local strategies and local implementation mechanisms for RE projects will be developed for the deep-dive cities under the 100 % RE project by February 2023. The 100 % RE scenarios shown in this report are the result of intensive cooperation of Fraunhofer ISE, ICLEI, and local stakeholders. Preliminary scenario results have been presented several times and discussions afterwards have helped to establish a common understanding of meaningful scenarios. The overall structure of the process is shown in Figure 1.

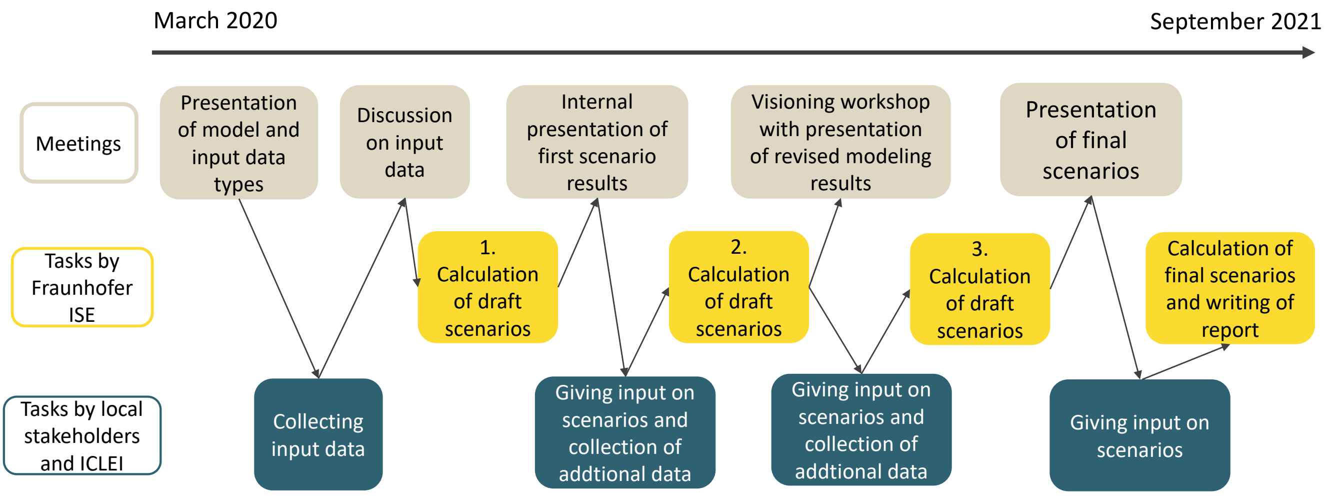


Figure 1: Structure of the process of energy system modeling between the different stakeholders

The outline of this report is as follows. Chapter 2 gives a short overview about the project and the deep- dive city of Avellaneda, Argentina which is the focus city of this report. In Chapter 3, a detailed description of the model is given including the scope of the model, its advantages, and its limitations. All used input data for the model as well as used sources and assumptions to calculate these input data are presented in chapter 4. Different scenarios are calculated to show the robustness of the different options, described in Chapter 5. The final scenario results are presented in Chapter 6 together with a transition plan for the leading scenario and a risk analysis linked with recommendations for how to overcome these risks. In Chapter 7 a short summary of the most important findings is given.

2.1 Energy supply and demand situation in the three countries

2.1.1 Argentina

In Argentina, the energy sector was privatized as part of the 1992 energy reforms. As a result of this restructuring, most energy production, transmission, and distribution fell into private hands. Only the state-owned nuclear power company and two hydroelectric plants still belong to the public sector (Pollitt 2008).

As one of the main producers of natural gas and oil in South America, Argentina meets about 75 % of its total electricity demand from fossil fuels. The share of renewable energy in electricity generation decreased from 36 % to 25 % between 1990 and 2019 due to a combination of rising electricity demand and rather constant renewable energy supply. The largest contributor to this share of renewables is hydropower, which covers about 20 % of electricity demand (in 2019). Excluding hydropower, renewable electricity generation has a share of only 5.3 % (in 2019).

Looking at the total primary energy consumption of Argentina, fossil fuels contribute to about 91.7 % and RE to 8.3 % (from Hydropower 3.5 %; biomass/waste 4.6 %; and geothermal, solar, wind 0.16 % (in 2018). (International Energy Agency 2021)

In Argentina, there are still quite a few tax breaks for companies investing in oil and gas production. Also, actual subsidies in energy are remarkably high, covering almost the 80 % of the total generation cost. This has a direct impact in the renewable energy projects, retarding the return on investment.

2.1.2 Indonesia

Perusahaan Listrik Negara (PLN) is a state-owned company that controls power generation, transmission, and distribution in Indonesia. The power generation market is open to private and independent power producers, but they must sell their power to PLN. However, the National Bureau of Asian Research has made the following assessment: "Despite loud calls for infrastructure development along the value chain, PLN's limited capacity and poor liquidity, caused by rising generation costs and subsidies, have prevented any development." (Bravo et al. 2015) Clearly, reforms and a transformation of the energy sector in Indonesia are needed.

Indonesia faces the challenge of meeting its national climate change target in the energy sector on the one hand, and meeting the increasing energy demand for the country's economic growth on the other. The country's archipelagic location also makes it difficult to distribute energy evenly.

Indonesia is currently heavily dependent on fossil fuels, which account for 64.2 % of total energy consumption. RE's share to date has come from geothermal, wind and solar (10.4 %), hydropower (0.8 %), biodiesel, and waste (14.5 %) (in 2018). (International Energy Agency 2021)

These existing renewable sectors have the potential for further expansion. However, given growing energy demand and national emission reduction commitments, these sectors need to be complemented by decentralized RE solutions such as those supported by this project.

2.1.3 Kenya

Kenya Power owns and operates most of the power transmission and distribution systems in Kenya. The government holds a majority stake of 50.1 % in this company and private investors hold a 49.9 % stake (Kenya Power 2015).
Kenya Electricity Generating Company Limited (KenGen) is the largest electricity-producing company in Kenya, managing about 80 % of the installed capacity for electricity production. The company uses various energy sources for electricity production, from hydropower to geothermal and wind. Due to the reform of the Kenyan power system in 1997, KenGen was decoupled from Kenya Power. Now 70 % of KenGen's shares are owned by the Kenyan government. Both Kenya Power and KenGen are listed on the Nairobi Securities Exchange. (KenGen 2021)
An analysis of the national energy supply mix shows a heavy reliance on fuelwood and other biomass, which account for 65.4 % of total energy consumption. Oil has a 16.4 % share, coal 1.9 %, hydropower 1.1 % and Wind, PV and other low-carbon sources about 15.1 % (all in 2018).
Renewable energy sources have a high share of electricity generation in Kenya. In 2018, this was 83 %, with about 30 % hydropower, 40 % geothermal, 11 % wind, 1.7 % solar, and 1.4 % bioenergy (International Energy Agency 2021).
In 2018, 75 % of the population had access to electricity, and the government has a stated goal of 100 % access by 2030. Much of the progress in the last years can be attributed to solar home systems. (Alliance for Rural Electrification 2019)
Kenya currently has one of the most active markets for commercial solar photovoltaic (PV) systems compared to other developing countries. This increases the potential for access to affordable RE technologies. The government is waiving the 16 % VAT on all solar products to make them more attractive, especially for rural, sparsely populated, arid, and semi-arid areas. (Munyaka and Becker 2016)

2.2 Case study Avellaneda

The city of Avellaneda was chosen as the deep dive region for Argentina. Avellaneda is a town in the Province of Santa Fe and lies 630 km direct distance north of the capital Buenos Aires. Some key facts are summarized in Table 2. More information about Avellaneda can be found in Perpétuo et al. (2020).

Table 2: General information about Avellaneda, Argentina (Perpétuo et al. 2020)

Location	Argentina, Province of Santa Fe Latitude: 29° 07’ 03” S Longitude: 59° 39’ 03” O
Size	937 km² of which 7.6 km² is urban area
Currency	Argentinian Pesos (Exchange rate: 1 ARS = 0.008602 EUR)
Population	30,897
Climate	Mean outside temperature: 20.1 °C Average annual rainfall: 1260mm (rainy season in spring-summer)
Main economic activities	Agricultural activities (mainly livestock and field cultivation), cotton production
Grid electrification rate	100 %

Avellaneda’s electricity supply is based on imports from the national energy system and one biogas CHP with an installed electric capacity of 6 MW and an electrical output in 2019 of 60.9 MWh.

3 Energy system modeling with KomMod

The energy system optimization model 'KomMod' identifies the cost minimal combination of supply technologies for an energy system, given specific goals and defined boundary conditions. KomMod takes the dynamics of the system into account by optimizing the entire energy system (electricity, heating/cooling, and energy for transport) over one year in hourly temporal resolution. This enables the detailed representation of fluctuating energy sources and analysis and consideration of the feasibility of each technology.

As input data, KomMod requires demand profiles for electricity and heat in hourly resolution for one year. Furthermore, economic and technological parameters for all considered technologies are required as well as detailed information on the potentials of the available energy sources. Information on climate data is also required. For consistency, all data is projected for the target year– in this study, the year 2050.

The model optimizes the supply side of the energy system to achieve the minimal total costs of the energy system while adhering to the given constraints, such as the target share of renewable energy generation or the restriction on energy import or export. Total costs include investments, operation and maintenance costs, as well as fuel costs, if applicable. The results provide data on the optimal capacity of each technology to be installed as well as an optimal hourly operation plan. Additionally, the temporal profile of import and export of electricity is calculated in case the local units are not capable of covering the energy demand at all times, or are generating surpluses.

Mathematically, the optimization is done by setting up a linear equation system which then is solved by the Simplex algorithm. Besides the physical and economic descriptions of each technology, there are some main equations forming the equation system. The central equation is named the objective function and defines the goal of the optimization. In this study, it aims to minimize the levelized total annual costs of the energy system. The most important physical equations are the energy balances for electricity and for heat for each temperature level. They combine the energy output, restrictions and conditions of each technology with the given demand in each sector. Accordingly, these equations incorporate the relevant occurring interdependencies. They assure that the given energy demand for each sector is covered in every hour of the year.

A graphical representation of the model is given in Figure 2. The energy sources used are depicted on the very left side of Figure 2, these are mainly renewable energy sources, but the utilization of fossil fuels is also possible. Wind energy, photovoltaics and hydro power resources and conversion are summarized in the figure and not shown separately. All other conversion technologies are depicted in the middle part of the figure. In the left column, all conversion technologies producing either heat, cold, or electricity out of the different resources are shown. In addition to combined heat and power (CHP) plants, which produce heat and electricity by converting different kinds of fuels like biomass, biogas, or even fossil fuels, there are boilers, heat pumps, power-to-heat and chillers using either heat (absorption) or electricity (compression) to produce cold.

In the middle column, different technologies producing or using synthetic fuels are depicted. Electrolyzers use electricity to produce hydrogen and excess heat from the exothermal process. This hydrogen can be either used directly in the transport sector or in industry, but it can also be stored and later converted to electricity again with fuel cells, or it can be used to produce other synthetic fuels like methane or methanol. To produce these synthetic fuels, carbon dioxide is needed, in addition to hydrogen. This carbon dioxide can be either extracted from the air via direct air capture or extracted from exhaust gases from combined heat and power plants. Both extraction processes as well as the synthesis processes need heat and have certain losses. Although producing methane and methanol is much more energy-intensive than producing hydrogen, still it has some advantages. Methane can be used in the same way as

natural gas and therefore fed into a gas grid or used in a gas power plant. Methanol is a liquid fuel which is easier to store and transport. Overall, hydrogen is quite hard to handle as it is very volatile. As it has a low density it must be compressed to at least 200 bars to be transported, and it is easily flammable.
In the last column, all storage technologies implemented in KomMod are depicted. These are electrical storages, mainly batteries, but also possibly hydro storages; heat and cold storages; and fuel storages for hydrogen as well as other fuels that have been produced and shall be used at a later time. In the very right of the figure, the different consumer types are shown. Normally these are households, commercial enterprises, industries, and the transport sector. It should be noted that for electricity all demands are summed up in the model to one demand time series that has to be covered at every hour of the year, because in the model the grid is seen as ideal and no transmission restrictions for any energy type are taken into account. For heat, different types of heating demands can be implemented in the model and they can be assigned to different technologies. For the specific case of Avellaneda besides commercial heating demand, cooking demand is prevalent. These demands are covered by different technologies and are therefore implemented in the model separately.

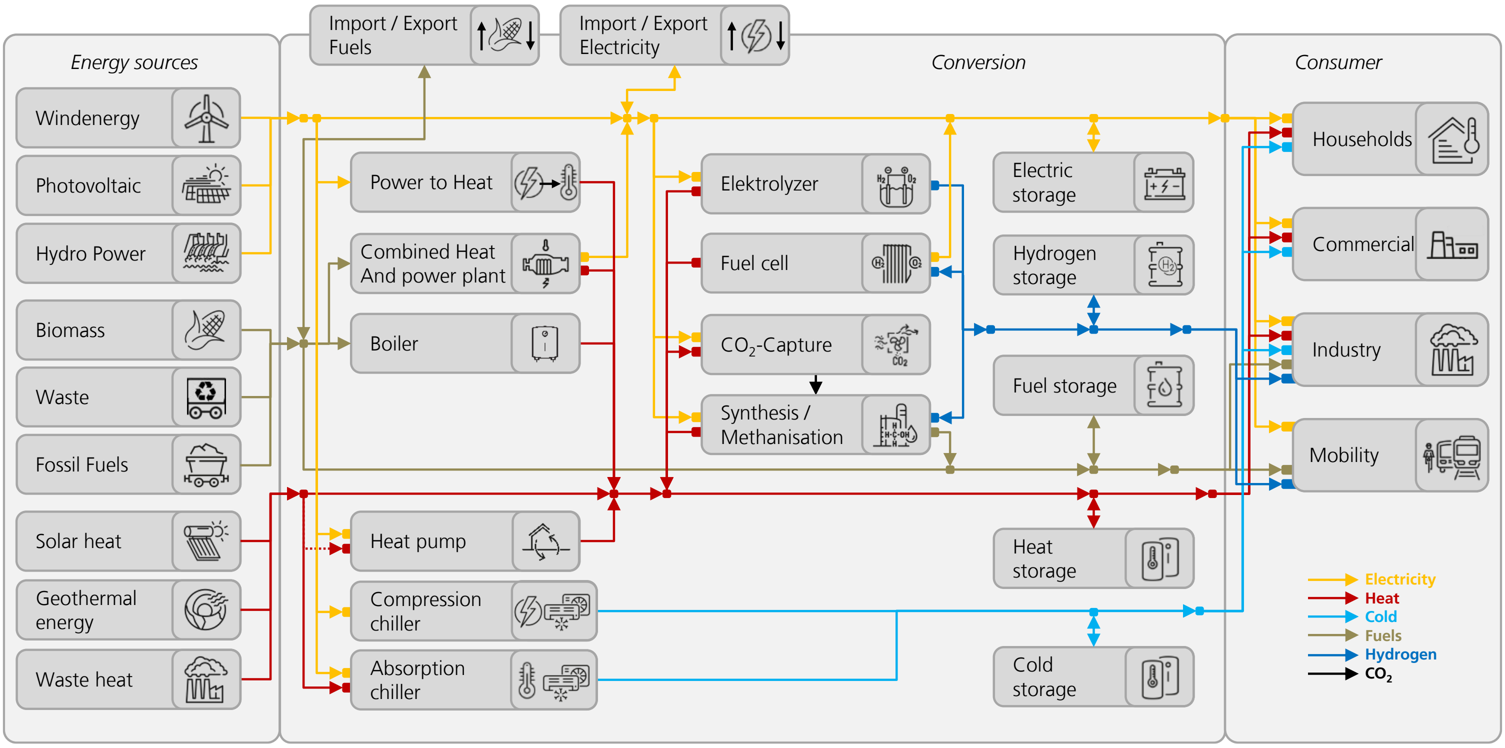


Figure 2: Graphical representation of the model KomMod with all technologies included

KomMod minimizes, and therefore considers, total system costs. As described above this includes capital costs and operation and maintenance costs for all technologies as well as fuel costs, costs for the import and export of energy, if applicable, as well as possible costs for carbon dioxide emissions. But there are costs of "real" energy systems which lie outside the scope of the model which is the reason why the modeling results should be interpreted as stylized scenarios showing possible options for future energy systems. Costs that are not included in the model are, for example, network charges as well as grid expansion costs or profits for energy providers.

4 Input data

In chapter 4.1 all energy demand projections are described in detail, including the applied time series. The potentials for all applicable kinds of renewable energy technologies are described in 4.2, while all used costs data is stated in chapter 4.3. In the last subchapter 4.4 the used weather data is presented.

4.1 Energy demands today and projections

All relevant demand sectors are included in the scenarios, with exception of aviation (see chapter 4.1.6). It is assumed that cooling demand is included in electricity demand (see chapter 4.1.5) and therefore met with compression chillers. In the following subchapters, the demand projections for every demand sector are summarized with all used sources and calculation steps. In the last subchapter (4.1.7) a summary of the total resulting energy demand today and in 2050 is given.

4.1.1 Macroeconomic developments

Data on population and specific GDP development is available for the years 2020 (actual) and 2025 and 2030 (projections) as well as the average annual growth rates for the years 2015-2020 (IPEC 2021). With this data population and GDP between 2015 and 2020 is being calculated and then all data points are extrapolated with a linear development until 2050. The results for population development are depicted in Figure 3. As the historic as well as projected development until 2030 is linear, a linear extrapolation until 2050 seems reasonable and leads to a population of 45,025.50 in 2050 and 14,070.47 households with a household size of 3.3 (value for today).

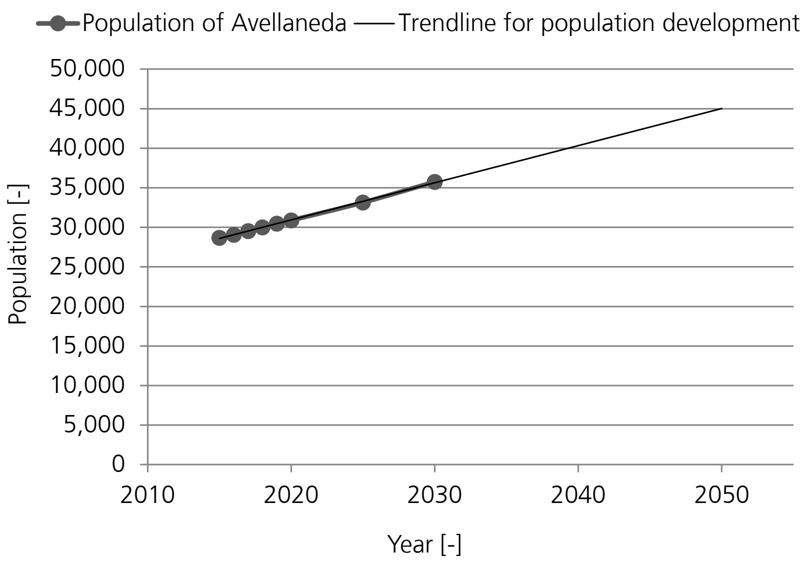


Figure 3: Historic and future development of population in Avellaneda, own representation based on IPEC (2021)

The GDP development is depicted in Figure 4. Absolute GDP values are calculated out of the specific ones with the population data. Specific GDP decreased from 2015 until 2020 with a growth rate of -0.4 % per year, but the projection shows an increasing trend. To account for a flattening increase of GDP for the time span 2030-2050, the development from 2015 until 2030, not 2020 to 2030, is extrapolated.

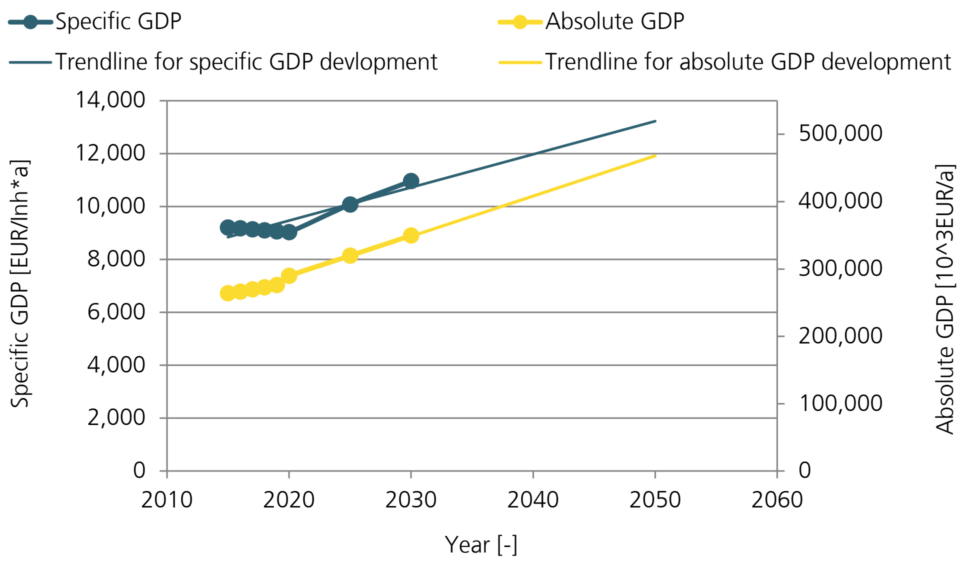


Figure 4: Historic and future projected GDP development in Avellaneda, own representation based on IPEC (2021)

4.1.2 Electricity demand

The electricity demand of Avellaneda is known for the years 2014 until 2019 (COSEPAV 2020b) and shown in Figure 5.

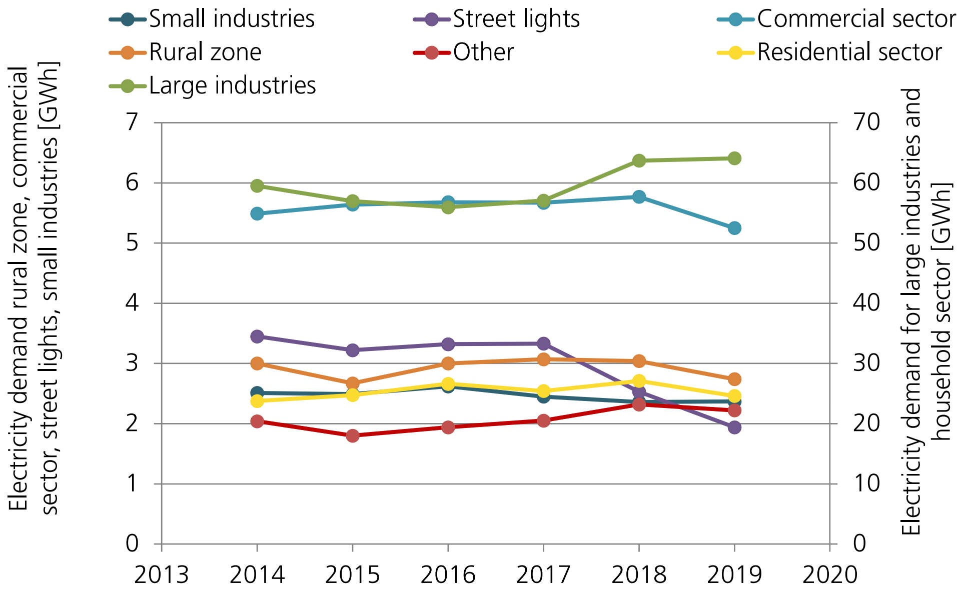


Figure 5: Electricity demand in different sectors for the years 2014-2019, own representation based on COSEPAV (2020b)

As electricity demand in large industries and the residential sector (green and yellow) is much larger than the others, they are shown on the second y axis on the right. For a better depiction of the shares of the different sectors, refer to Figure 6, which depicts the shares of the different sectors for electricity demand in the year 2019.

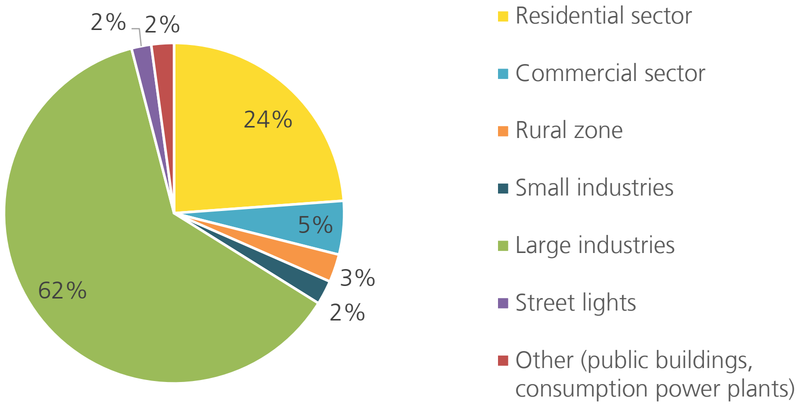


Figure 6: Shares of different sectors on overall electricity demand in the year 2019, own representation based on COSEPAV (2020b)

Large industries have by far the highest share with 62 %; households come second with 24 %. However, no information about the future development of single sectors is given; therefore, it was decided to project the total electricity demand using indicators. Three different indicators are used to project electricity demand in 2050 (see Figure 7), and the results are compared. The highest electricity demand in 2050 is projected when the total GDP is taken as indicator (180 GWh), with capita and GDP per capita the results are close to each other and lower than the former (capita: 152 GWh, GDP per capita: 146 GWh). For the base scenario the demand projected with capita is taken as it lies in between the two others. In a second demand scenario this demand is multiplied by 1.3 resulting in a demand of 197 GWh.

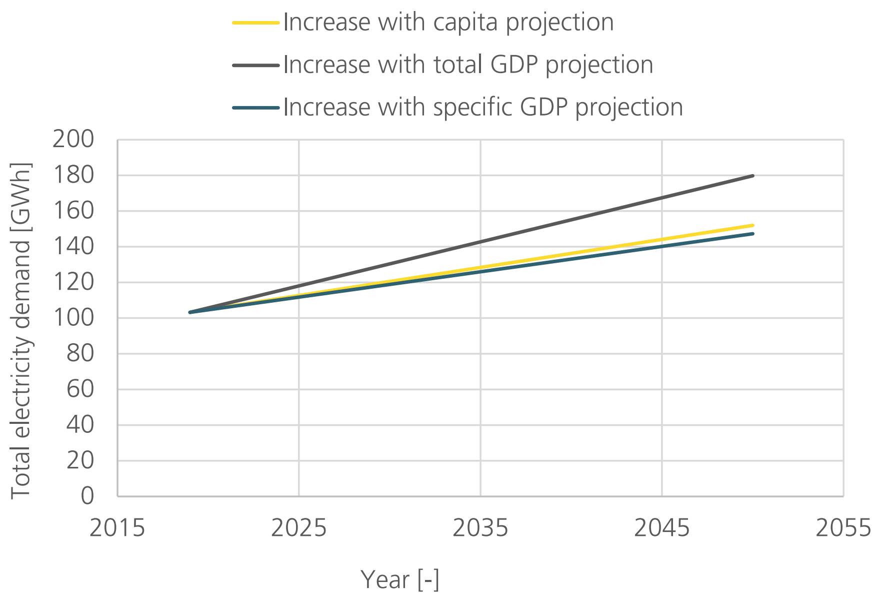


Figure 7: Electricity demand projection with three different indicators: capita projection, specific GDP projection and absolute GDP projection, own elaboration using data from IPEC (2021)

Comparing the specific electricity demands shall help to judge on a realistic increase of electricity demands until 2050. For this purpose, the specific electricity demands for 2050 are compared to the specific demands today for Germany and the specific demands of the other two case studies (Kisumu in Kenya and West Nusa Tenggara in Indonesia) (see Table 3).

Table 3: Specific electricity demands in Avellaneda and the other two case studies today and in 2050 in comparison with specific electricity demands today in Germany

	Specific electricity demand calculated with total demand	**Specific electricity demand calculated with residential demand**
	[kWh/cap]	[kWh/cap]
Avellaneda today and 2050 as correlated to capita development	3387	807
Avellaneda in 2050 with high demand scenario	4403	1049
West Nusa Tenggara in 2019	385	242
West Nusa Tenggara in 2050 according to different projections	1824-4183	673-1633
Kisumu in 2015	227	3.2 (81.7 for connected households)
Kisumu in 2050 in mean demand scenario	1050	315 (assumption: 30 % of ec demand for households)
Germany in 2019 (Bundesministerium für Wirtschaft und Energie 2021)	6237	1558

Germany is used as a reference for an industrialized country with a high electricity demand. As values for Germany are for today, it should be questioned how electricity demand (transport and heating not included) shall develop until 2050, in most studies it is projected that it will decrease (e.g. (Sterchele et al. 2020); without electricity for transport sector).

The projected electricity demand of Avellaneda is the highest from the three case studies in the 100 % RE project, while the high projections for West Nusa Tenggara still lie in the same order of magnitude. Germany's electricity demand today is higher but heavily influenced by industrial energy demand from energy intensive industries like steel, automotive, cement, etc. It seems reasonable that electricity demand is therefore higher in Germany, especially as a decrease until 2050 is assumed. The same holds true for specific electricity demand in households in Germany, which is higher than the projected electricity demand for Avellaneda, which can be attributed to higher incomes and GDP.

Time series of electricity demand is given for the time span September 2019 until August 2020 in 15 min timesteps (COSEPAV 2020a). In order to use this data in the model, it is aggregated to one-hour timesteps and transformed to one calendrical year, which means that the order of the months has been changed to: January 2020- August 2020 followed by September 2019 until December 2019, in addition the weekdays have been adjusted so that the 2019 data fit to the year 2020.

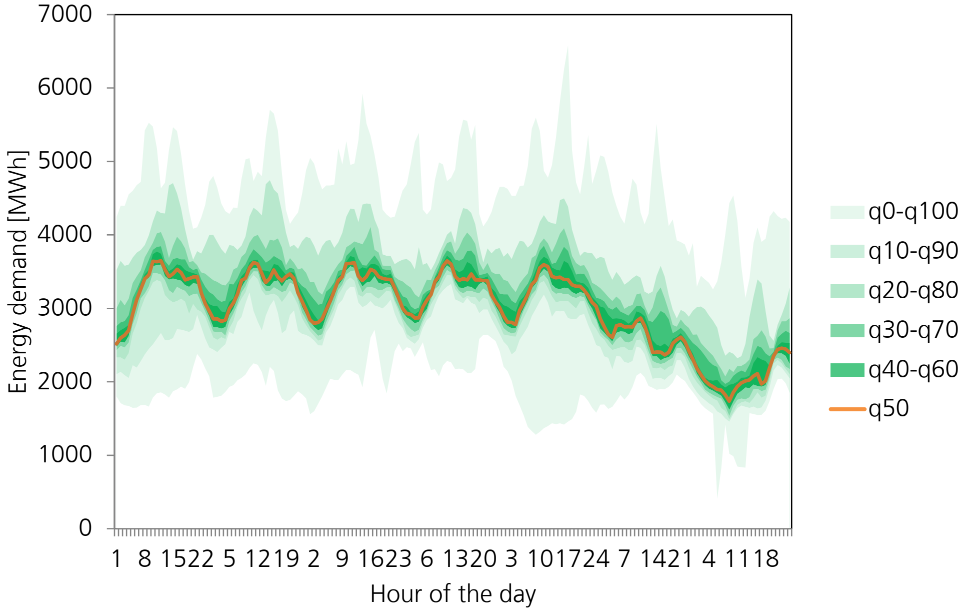


Figure 8: Distribution of the electricity demand shown in deciles (Monday until Sunday), own elaboration based on COSEPAV (2020a)

In Figure 8 the distribution of electricity demand in deciles is shown. In this diagram electricity demand for all 52 weeks of one year is taken, and it is calculated which percentage of the values for every hour of the week are in a certain range. The 0,5 decile, named q50, is the median, which means that 50 % of the values are below the shown value and 50 % are above. The same definition holds true for the other deciles. For example, the q30-70 means, that 30 % of all values (the 30 % lowest ones) are below the shown respective area and 30 % are above (the 30 % highest ones). The load profile shows lowest values at the weekend, especially on Sunday, as electricity demand is largely dominated by the demand of large industries which seem to partly shut down the production on the weekend, as demand is dropping by approximately 50 % on Sunday. During the week, demand is lowest in the night hours and has the highest peak around noon and two smaller peaks in the afternoon (5 pm) and evening (9 pm). The peak in the afternoon could be the moment when everybody comes home from work, the peak in the night could be when dinner is served, lights or television devices are switched on.

4.1.3 Households' energy demand for fuels

Households use bottled gas or are connected to a gas grid to cover cooking, heating and warm water demand. For both user groups, consumption data is available (SyESA GAS 2020). At the time of data collection, a total of 2020 households were connected to the gas grid, available consumption data has a temporal resolution of 2 months and is given for the time span 2014-2019. Figure 9 shows the mean bimonthly consumption of one household. The red line marks the lowest consumption, which is prevalent in the summer months. It is assumed that the reason for this is high outside temperatures causing less to no use of gas for heating. This means that all consumption above that red line is assigned to heating purposes, while all consumption below that red line is assigned to cooking and warm water usage. The demand above the red line is correlated to a mean outside temperature for every two-month period; the result is shown in Figure 10. The coefficient of determination R^2 can be used to measure how well two parameters are correlated with each other, and therefore helps to understand if the assumed gas consumption for heating is correlated to the outside temperature, which would be a strong indicator that the assumption that all gas consumption above that red line in Figure 9 can be assigned to heating. R^2 is 0.84 in this case, with a value of 1 showing perfect correlation between two parameters and a value of 0 showing no correlation between two parameters.

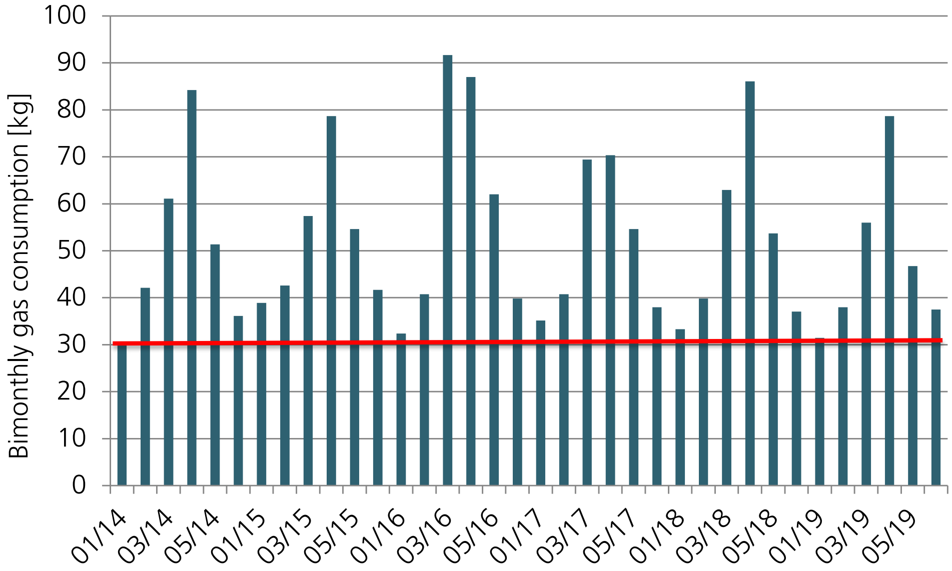


Figure 9: Mean bimonthly gas consumption of one household connected to the gas grid according to SyESA GAS (2020)

Therefore, a satisfying correlation between outside temperature and assumed gas consumption for heating is given. The next assumption used to divide gas consumption into cooking, heating and warm water is that households who use bottled gas use it only for cooking purposes, this assumption is a result from internal discussions with the local stakeholders. The consumption of bottled gas for one year is given for 42 households and varies between 40 and 180 kg and is partly attributable to the household size which is also given for that households (see Figure 11).

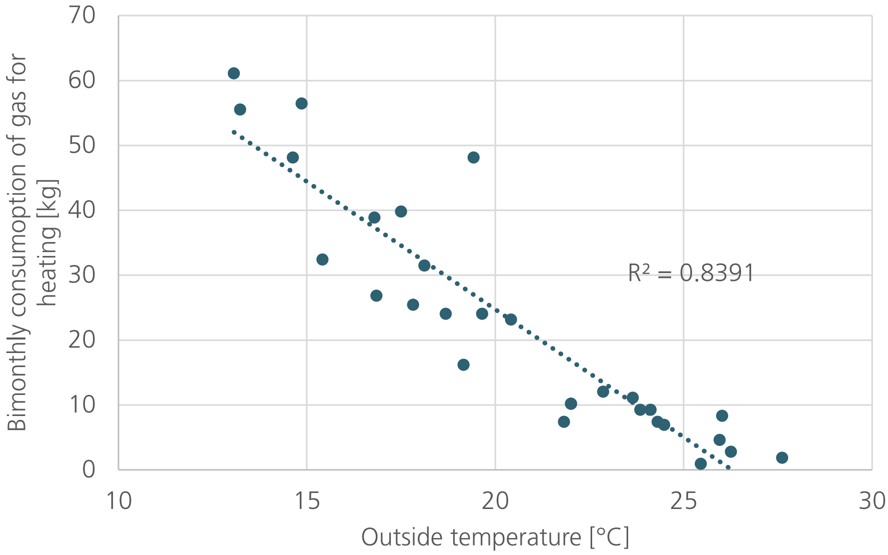


Figure 10: Correlation between outside temperature and assumed gas consumption for heating purposes, own elaboration based on data from SyESA GAS (2020)

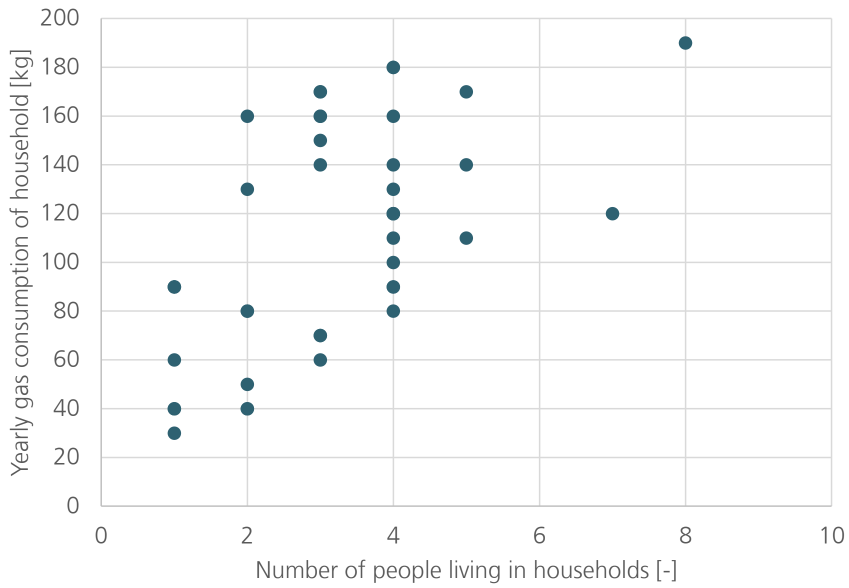


Figure 11: Yearly gas consumption of one household over number of people living in the households for bottled gas, own elaboration based on data from SyESA GAS (2020)

As no additional information about the households and their consumption behaviour is available, the mean consumption per person is calculated, and from that the mean consumption per mean household, which has 3.3 members. Furthermore, it is assumed that gas consumption for cooking is the same in households connected to the gas grid and households using bottled gas. As gas consumption for heating and cooking for one household are then assumed to be known, the remaining gas consumption in grid connected households can be assigned to warm water usage. This leads to the following amounts of gas for cooking, heating and hot water (Table 4). Originating from the gas consumption, the end energy demand for the three purposes has to be calculated which is done with a factor of 0.8. The demand in 2050 is calculated with the projection of population, a constant value for the number of household members of 3.3, and the assumption that the end energy demand for all three purposes for one household will stay constant from today until 2050.

Table 4: Yearly gas consumption of one household for cooking, heating and hot water, own elaboration

	Gas consumption [kg]	Short description on calculation
Gas consumption for cooking	110	Gas consumption of households using bottled gas
Gas consumption for heating	100	Gas consumption above base load (see Figure 9)
Gas consumption for hot water	90	Remaining gas consumption of grid connected households

For all three purposes, time series are needed for the implementation in the model. For warm water, a constant time series throughout the year is assumed, which is a simplification as demand for hot water will be higher in winter than in summer. For cooking, a simple cooking profile is set up according to internal discussions in the project team which is shown in Figure 12.

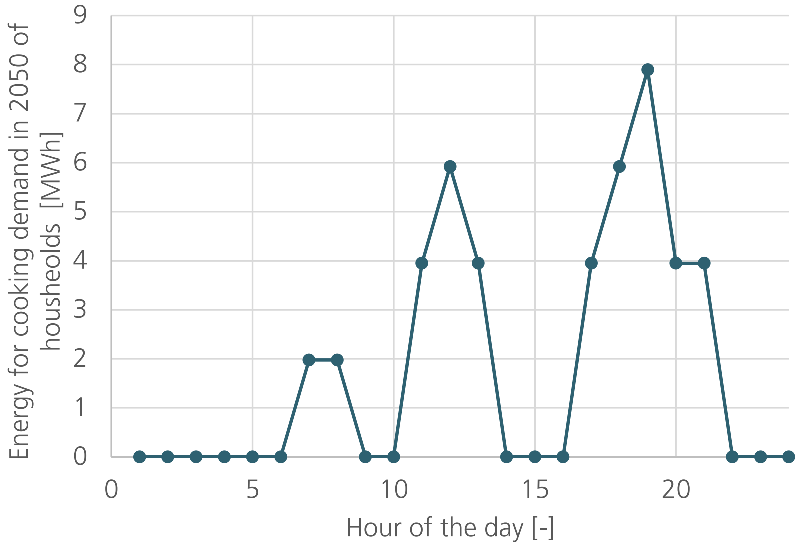


Figure 12: Energy for cooking demand in 2050 in households in [MWh] time series for one day, own elaboration

For times series of heating demand, a method based on heating degree days is used which is distributing the yearly heating demand based on information about target inside and outside temperature. Outside temperature is known from historic weather data, but no information about target inside temperature is given. As information about the bimonthly gas consumption for heating purposes is available, target inside temperature is chosen so that bimonthly gas consumption from historic data and from synthetic hourly heating demand time series match. This leads to the heating time series for one year shown in Figure 13.

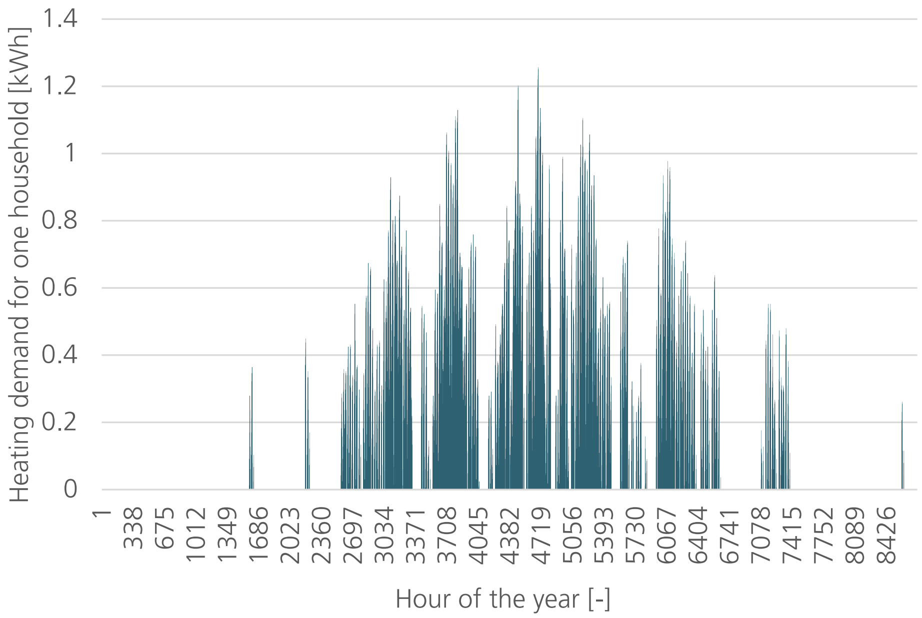


Figure 13: Hourly time series for heating demand of one household, own elaboration

4.1.4 Cooking, heating and commercial and industrial fuel demand

Gas is also used in the commercial and industrial sector, but no information about gas consumption in these sectors is available. Therefore, the gas demand can only be estimated roughly. More data is needed here so that further planning processes can be based, not on estimations of energy demand, but actual measurements. For the scenarios in this study, it is roughly assumed that the ratio between electricity demand and gas consumption is the same in commercial and industrial sector as in households. In addition, also the usage forms are based on assumptions. The results are shown in Table 5. The time series for the usage forms of cooking, warm water and space heating are the same in households and commercial and industrial sector, time series for heating demand for other purposes like process heating demand is constant throughout the year.

Table 5: End energy demand for cooking, warm water, space heating and heating for other purposes, own elaboration

	Sum [GWh]	Cooking [GWh]	Warm water [GWh]	Space heating [GWh]	Heating for other purposes [GWh]
Households	43	16	13	14	0
Large industries	106	0	0	35	71
Commercial and other	22	0	6	7	8

4.1.5 Cooling demand

No information on today's cooling demand is available, and no studies on the future development of cooling could be found during desk research. It is assumed that cooling demand is included implicitly in the electricity demand.

4.1.6 Energy demand for transport sector

Number of vehicles and passenger kilometers are given for the year 2019 (Registro del Automotor Seccional 1 2020). Development of the number of cars and buses is projected in Aliano et al. (2019) for the whole of Argentina until the year 2050. This projection is used, with the assumption that the number of vehicles in Avellaneda will increase with the same gradient as projected nationwide. As Aliano et al. (2019) are only stating projections for cars and buses, but data for Avellaneda provides information about 6 different motorized vehicle types, it is assumed that the number of motorcycles and taxis will increase with the same gradient as projected for cars and the numbers of trucks and vans is increasing with the same gradient as projected for buses. Furthermore, it is assumed that the driven mileage of the different vehicle types will remain the same until 2050. For cars, scooters, taxis and vans an electrification rate of 100 % is assumed. Buses and trucks will be partly fueled with hydrogen. It is still discussed which range must be achieved by electric trucks and buses to ensure economically feasible operation. Electric buses and trucks in comparison to buses and trucks using synthetic fuels have the advantage that energy demand is lower, as they can use electricity directly, while hydrogen trucks and buses have a higher range, but energy demand is higher. Assuming 50 % hydrogen trucks in Avellaneda in 2050, the estimation of energy demand is to the safe side. Table 6 shows the projected number of different vehicle types and percentage of electric and hydrogen vehicles in 2050.

Chapter 6.4 describes the risk analysis of the transition of the transport sector while energy demands of different vehicle types are given in Appendix B.

Table 6: Projected number of vehicles in Avellaneda in 2050 as well as mileages and shares of electric and hydrogen vehicles, own elaboration based on data named in preceding paragraph

	Absolute number of vehicles	Mileage for one vehicle per year	Percentage of electrified vehicles (assumption)	Percentage of hydrogen vehicles (assumption)
Cars	16,673	13,330	1	0
Scooters	30,795	18,000	1	0
Taxis	159	23,000	1	0
Buses	20	39,500	0.9	0.1
Vans	1,427	39,500	1	0
Trucks	1,289	39,500	0.5	0.5
Sum	50,363			

Hydrogen and synthetic fuels have no time constraints on their production, only that the total amount demanded in a year must be produced throughout the year. For electric vehicles, a simple charging time series is taken which is shown in Figure 14. For this time series, it is assumed that most vehicles are charged in the evening hours when people come home and vehicles are not used anymore.

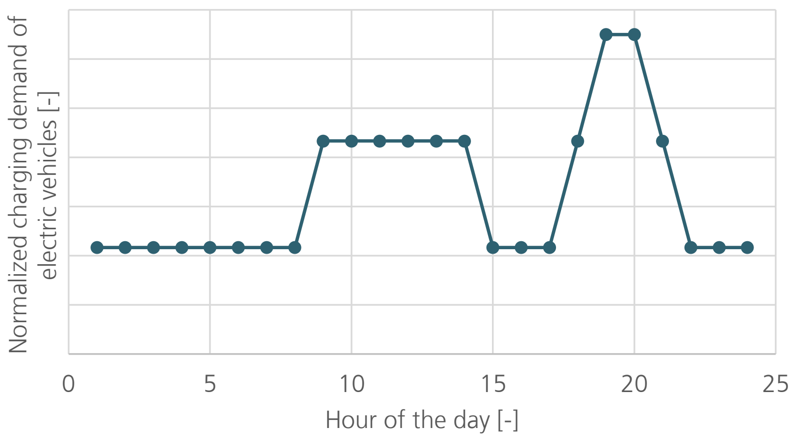


Figure 14: Normalized charging electricity demand for electric vehicles for Avellaneda in 2050, own elaboration

4.1.7 Energy demand today and in 2050

Energy demand today and in 2050 is depicted in Figure 15. It should be noted that gas demand in the commercial and industrial sector is not known for today and gas demand in households is only known for a part of all households. So, todays data on energy demand is partly based on the same assumptions as energy demand in 2050. Energy demand will increase by 17 % from today until 2050 in the base scenario and by nearly 55 % in the high demand scenario.

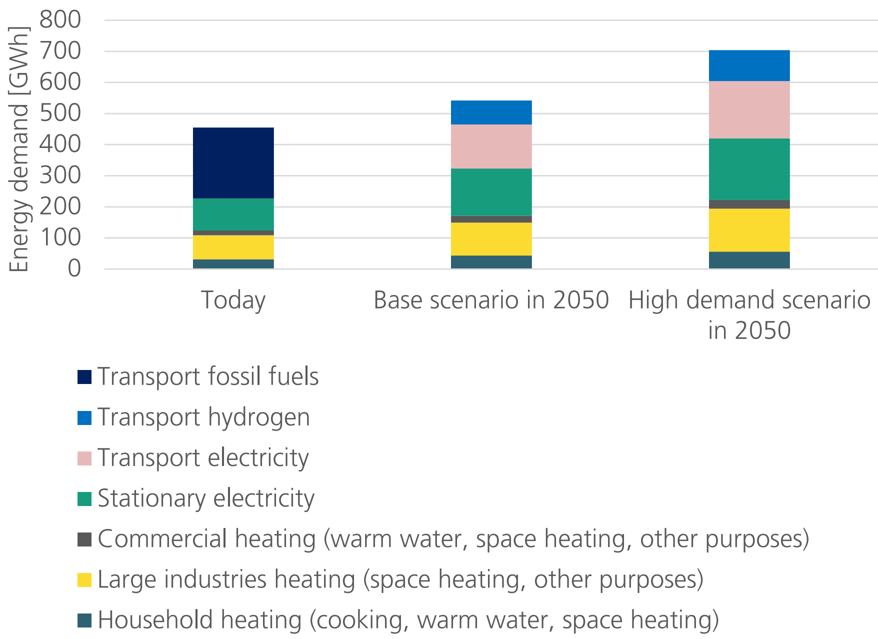


Figure 15: Energy demand today and in the two demand scenarios for 2050, own elaboration

4.2 Renewable energy potentials

In the following chapter, data processing for the evaluation of all different renewable energy potentials are described in detail.

4.2.1 Wind energy and Free field photovoltaic potential

The assessment of the potential for solar photovoltaic power plants and wind power plants is based on GIS data that has been compiled as part of the 100 % RE project (Sartorio 2021). The GIS data has one layer stating suitability for agricultural usage (named: "Capacidad productiva"). It is best to install wind power plants and free field photovoltaic on areas which have a low suitability for agricultural usage to avoid competition between food and energy production. Parts of Avellaneda in the east are not suitable for agricultural usage because they are regularly flooded by the nearby river. These areas can't be used for the installation of any power plants either and are excluded from the analysis. The best compromise is to use the areas classified with the letter C, which have medium suitability for agricultural use but don't flood. This area is 119 km² which leads to the potentials for wind power plants and free field PV shown in Table 7.

Table 7: Potential area and resulting installable capacity for free field PV and wind power plants, own elaboration based on data from Sartorio (2021)

	Area 'C' from GIS layer productive capacity [km²]	Resulting Potential [MW]
PV free field	119	9520
Wind power	119	1819

For PV it is further assumed that the elevation of the PV modules leads to a factor of 0.4 from usable area to module area of PV. The efficiency per unit area is 200 W/m². For wind power plants, the distance between two power plants is 5 times the rotor diameter in the wind speed direction and 3 times the rotor diameter in the direction across the wind direction. With these values, an ellipsoid around every wind power plant can be calculated and based on that the number of wind power plants installable in a certain area. The chosen wind turbine is an Enercon E-160 EP-5 with a rotor diameter of 160m and a capacity of 4.6 MW (Enercon 2021) which is especially suitable for lower wind speeds as prevalent in Avellaneda (see also chapter 4.4).

4.2.2 Photovoltaic rooftop potential

The GIS data is also used for the assessment of rooftop potential, as it also gives information about the building area, which is correlated to the rooftop area. It is assumed that the usable rooftop area is 60 % (value proposed by ICLEI and local government) and the module area to rooftop area is 50 %, considering framing as well as elevation on flat roofs. Furthermore, it is assumed that the orientation of the roofs in the different cardinal directions is equally distributed. Therefore 25 % of the usable rooftop area is assigned to each cardinal direction, namely south, north, east, and west. This leads to the installable capacities shown in Table 8.

Table 8: Building area, usable rooftop area for the installation of PV and installable capacity of PV in each cardinal direction, own elaboration based on data from Sartorio (2021)

Building area [km²]	Usable rooftop area in each cardinal direction [km²]	Resulting module area [km²]	Installable capacity in each cardinal direction [MW]
1.75	1.05	0.52	26.26

4.2.3 Biomass energy potential

Different types of biomass are theoretically existent in Avellaneda, but not all of them are taken into consideration as fuel in the presented scenarios. Total forest area is known from the GIS data, but as wood is also used for other purposes and the potential is unclear, wood is not included as a possible fuel in the scenarios. Agriculture is an important sector in Avellaneda, with mainly sunflower, soybean, corn, sorghum, wheat, cotton and pasture crops (oats, alfalfa, moha) being cultivated (Perpétuo et al. 2020). But internal discussions revealed that crop residues remain on the fields and should not be included as potential for energy production in the scenarios. The included potential in the model comes from livestock: approximately 730.000 chickens and 30.000 cattle are held in Avellaneda, and biogas can be produced from their manure. In addition, municipal waste is available that can be used for energy conversion.

4.2.3.1 Manure

Avellaneda is an important producer of poultry, with approximately 730.000 chickens held (Perpétuo et al. 2020) of which 600.000 live in larger farms where chicken manure could be collected in the future (internal discussions with local stakeholders). Therefore 600.000 chicken are taken as input data in assessment of the usable potential. In addition, 30.000 cattle are held. The respective possible biogas yields are depicted in Table 9.

Table 9: Theoretical livestock potential, own elaboration based on data from Perpétuo et al. (2020)

	Livestock amount	Specific methane yield (Fachagentur nachwachsende Rohstoffe e.V. 2021) [m³/year*animal]	Methane yields in [m³]	Methane yields [GWh]
Chicken	600,000	1.64	984,000	8,856
Cattle	30,000	237	7,110,000	63,990

This theoretical potential implies that it is possible to collect all manure that accumulates. This may require a reconstruction of the stables to make collection more efficient. These considerations have to be part of further planning processes. In chapter 6 the used percentages of the whole potentials are shown. As Avellaneda has a gas grid installed which will serve all households latest by 2050, the idea is to use this gas grid in the future to distribute biomethane to the households to cover heating, cooking and warm water demand. This requires a further processing step from biogas to biomethane. The fuel costs for biomethane are set accordingly. (see chapter 4.3.2). Using this procedure, biomethane can easily be mixed into the gas grid as soon as it is available, and the percentage of biomethane in the grid can eventually be increased as supplies increase.

4.2.3.2 Waste potential

Collected waste in Avellaneda is 3570 t/a in 2019 (Perpétuo et al. 2020). As the amount of waste is correlated to the number of inhabitants, a specific amount of waste per capita is calculated (0.117 t/cap) and with information about the number of households in 2050 the amount of waste in 2050 is projected to be 5274.8 t. The assumed calorific value is 2.8 kWh/kg.

4.2.4 Summary of renewable energy potentials

A summary of the primary energy supply calculated with expected full load hours for PV and wind power is presented in Figure 16. The largest potential comes from biomethane produced out of manure because of high amounts of livestock. Potential for free field PV comes second. As the built-up area of Avellaneda is small compared to the rural area in Avellaneda rooftop PV potential is small compared to free field PV potential.

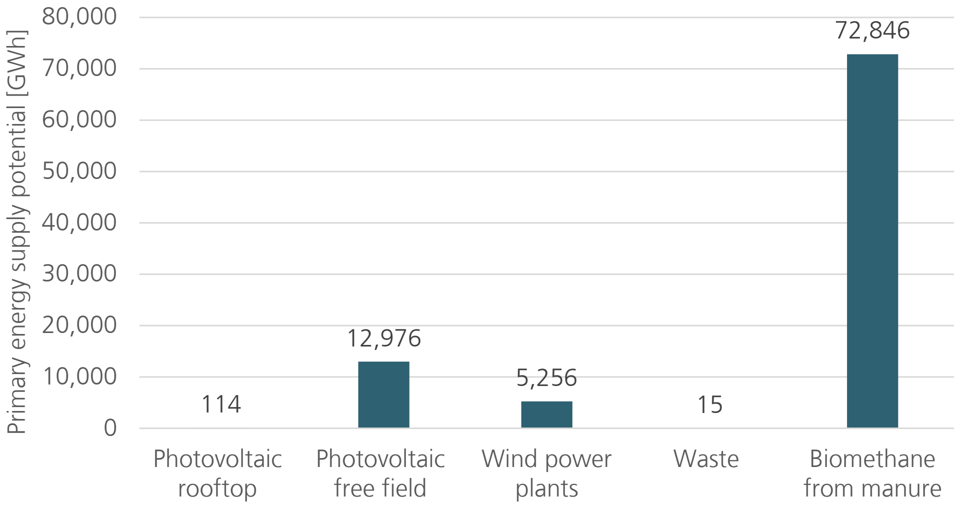


Figure 16: Primary energy supply potential of all renewable energy resources, own eleboration

4.3 Technology and cost data

4.3.1 Technology specific data

All technological specifications of the different power plant types are summarized in Table 10. Technology-specific data is taken from several references. As much as possible, data was taken from the same sources (Sterchele et al. 2020; Ram et al. 2019). Data was then cross-checked with other references. But data for all technologies are not available in Ram et al. (2019) and Sterchele et al. (2020), and therefore other references have been used as well, in accordance with the other two case studies from the 100 % RE project.

Table 10: Technology specific data for the scenarios (exchange rate from Nov. 2021)

	Full load hours	Efficiency	Investment costs [€2021/kW] ([ARS2021/kW])	O&M costs [% Investment]	Lifetime	References
Photovoltaics	1364	200 W/m², inverter: 98 %	508 (58,765)	2	30	(Sterchele et al. 2020; Ram et al. 2019)
Wind power plants	3031	Depends on wind speed	1117 (129,215)	2	25	(Ram et al. 2019; Sterchele et al. 2020; Perner et al. 2018)
Biogas power plants	0-8000	El: 40 % Th: 45 %	1818 (210,306)	3.8	30	(Ram et al. 2019; International Energy Agency)
Waste power plants	0-8000	El: 40 % Th: 45 %	4663 (539,416)	3.5	20	(Danish Energy Agency 2021)
Hydro power Plants	0-4000	92 %	3350 (387,528)	2	50	(Ram et al. 2019; Anciaux et al. 2018)
Oil power Plants	0-7000	El: 42 % Th: 20 %	921 (106,541)	8.5	30	(Ram et al. 2019)
Gas power Plants	0-7000	El: 63 % Th: 20 %	921 (106,541)	8.5	30	(Ram et al. 2019)
Heat pumps	0-8000	COP: 4	1218 (140,898)	1	20	(Sterchele et al. 2020)
Biogas boilers	0-8000	85 %	209 (24,177)	3	20	(Sterchele et al. 2020)
Biogas stoves	0-8000	45 %	354 (40,951)	3.8	20	(JIQ magazine on climate and sustainability 2016)
Electric stoves	0-8000	80 %	282 (32,622)	2	20	(Jeuland and Pattanayak 2012)
Electrolysis	0-8000	El: 64 % Th: 20 %	471 (54,485)	3	20	(Perner et al. 2018)
Hydrogen storage	-	Dis/charge: 0.1 % Self-discharge: 0.01 %	165 [€/kg] (19,087 [ARS/kg])	2.5	20	(Sterchele et al. 2020)
Batteries	-	Self-discharge: 0.03 %	101 [€/kWh] (11,684 [ARS/kWh])	1	15	(Sterchele et al. 2020)
Thermal strages		Self-discharge: 0.09 %	101 [€/kWh] (11,684 [ARS/kWh])	1.3	20	(Sterchele et al. 2020)

4.3.2 Fuel costs

Despite capital as well as maintenance costs for the different technologies, fuel costs are an important input parameter that can have a major influence on the results. Fuel costs make up a large share of the overall costs when fuel-consuming power plants supply high shares of energy. Because of that biogas fuel costs are varied in the scenarios to account for insecurity in fuel price prediction. For further information on this variation, refer to chapter 5.3. Table 11 depicts the used fuel costs in the different scenarios

Table 11: Fuel prices today and projections for 2050 (exchange rate from Nov. 2021)

Fuel	Fuel price today	Fuel price in 2050	References
Waste and manure feedstock costs	unknown	0.017 €/kWh (1.97 ARS/kWh)	Cost for collection assumed
Biomethane	unknown	0.017 – 0.051 €/kWh (1.97 -5.90 ARS/kWh)	(International Energy Agency 2020) for mean costs
Oil	unknown	0.0446 €/kWh (5.16 ARS/kWh)	(Ram et al. 2019)
Gas	0.01 €/kWh (1.16 ARS/kWh)	0.042 €/kWh (4.86 ARS/kWh)	Today: (globalpetrolprices.com 2021) 2050: (Ram et al. 2019)
Diesel	0.69 €/l (79.82 ARS/l)	0.69 €/l (79.82 ARS/l)	Today: (globalpetrolprices.com 2021) 2050: assumption
Gasoline	0.75 €/l (86.76 ARS/l)	0.75 €/l (86.76 ARS/l)	Today: (globalpetrolprices.com 2021) 2050: assumption

4.4 Climate data

Climate data is given to the model in the same time resolution as the demand time series, which is hourly. As source for climate data, Meteonorm, is used (Meteonorm 2012). Data for Reconquista weather station is taken, which is located as shown in Figure 17. Meteonorm provides synthetic climate data which are representative for a certain weather station in a certain time span. The used climate data is future data for the year 2050, incorporating effects of climate change.

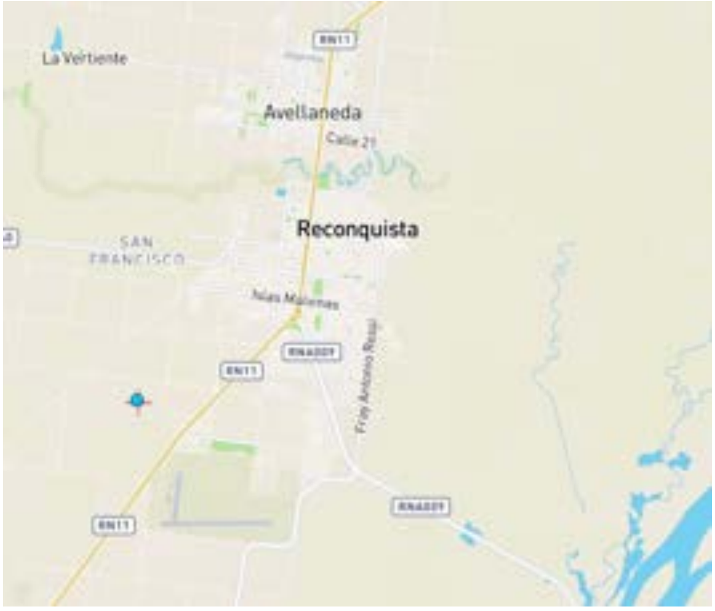


Figure 17: Reconquista weather station whose data has been used for the modeling, map from meteonorm (2012)

Temperatures in Avellaneda vary between 38.1 °C and -0.7 °C according to Meteonorm (2012) and have a mean of 20.31 °C. The annual sum of global solar irradiance on a horizontal plane is 1742 kWh/m². The time series (Figure 18) shows that irradiation is less in winter.

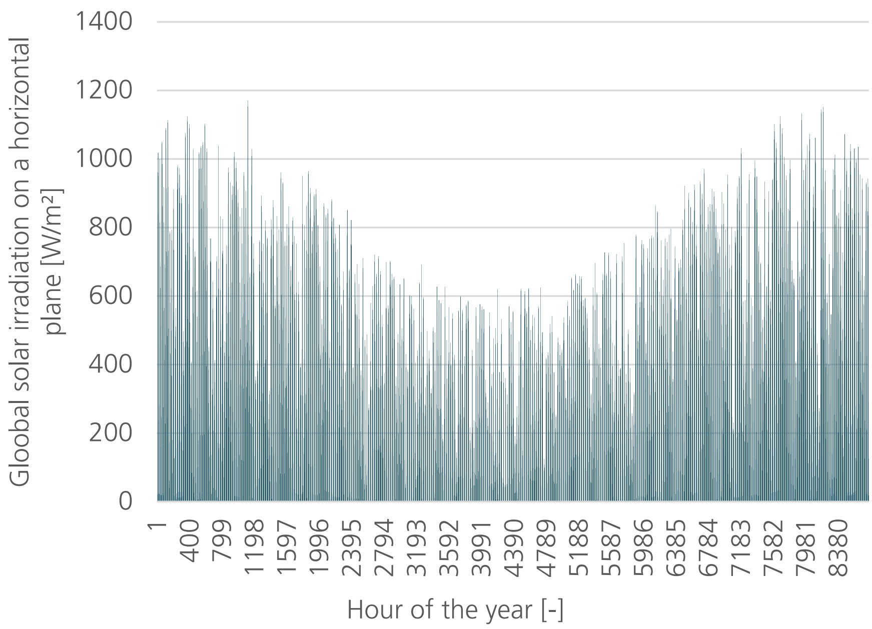


Figure 18: Solar irradiation global on a horizontal plane for Avellaneda (Meteonorm 2012)

A wind speed histogram at 100 m height for three different data sets is depicted in Figure 19.

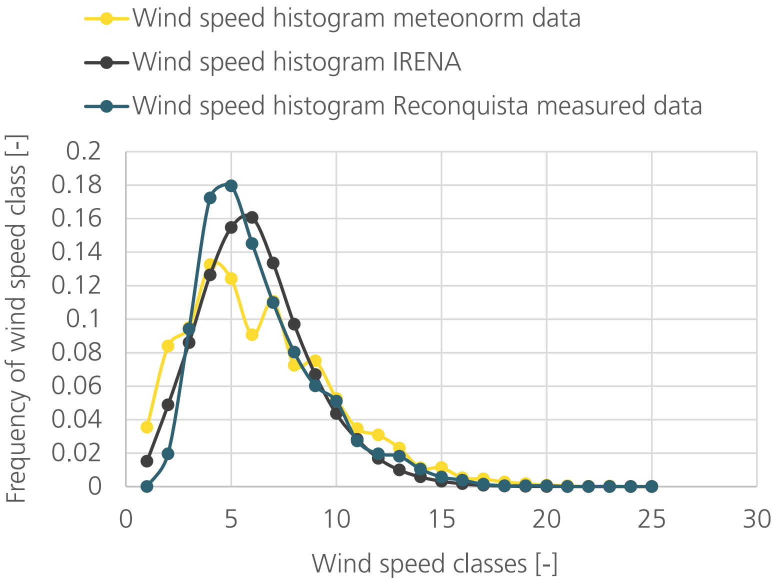


Figure 19: Wind speed histogram for the used wind data in 100m height (Meteonorm 2012)

The used wind speed data in the model is taken from Meteonorm (2012) as this is the only wind speed data available in an hourly resolution. As wind speed is given in 10 m height, the wind speed in 100 m has to be calculated via the equation $v_{100m} = v_{10m} * \left(\frac{100m}{10m}\right)^k$, with v being the wind speed in the respective heights and k being the exponent classifying the terrain around the measuring station which is 0.28 for terrain with obstructions lower or equal to 15m height like trees or buildings (Patel 2006). The results in histogram format are shown in yellow in Figure 19. This data is compared to two other datasets as validation. IRENA wind atlas data can be downloaded in histogram format at selectable height for every location of the world (Technical University of Denmark, IRENA 2021) and is depicted in dark grey in Figure 19. In addition, measured wind speed data for the Reconquista weather station in daily temporal resolution is available at 2 m height (Servicio Meteorológico Nacional 2020). To calculate the wind speed in 100 m height above shown formula is used again. The result is depicted in dark blue. It has to be noted that this formula can only serve as an approximation for the calculation of the wind speeds in other heights than measured, but as all three datasets show comparable wind speeds at 100m height, the data from Meteonorm (2012) is seen as sufficiently accurate to be used in the model.

5 Scenarios

In this chapter, first all considered technologies in the different scenarios are described (chapter 5.1), then all calculated scenarios are explained (chapter 5.2 - 5.5).

5.1 Considered technologies

The different technologies implemented in the model (see Figure 2) are assigned to different energy demand sectors that they can supply to (Figure 20). The technologies are chosen according to their potential use in Avellaneda. Some of the technologies shown in Figure 2 are therefore not implemented; these are solar heaters, power to heat, chillers, and cold storages, as well as geothermal and hydro power plants. Cooling demand is assumed to be part of electricity demand. Power to heat and solar heaters could supply to heat demand, but their usage has been tested at the beginning of the modeling process and their deployment wasn't economically feasible. For geothermal and hydro power plants no potential could be detected in Avellaneda.

Demand Sectors	Supply technologies			Storage technologies
Electricity	CHP using Biomethane (waste and manure)	Wind energy	Photo voltaics	Batteries
Commercial and industrial heat	CHP or boiler using biomethane (manure & waste)	heatpumps	Electrolysis	Heat storage
Cooking	biogas stove Manure or synthetic gas	Electric stove		
Hydrogen	Electrolysis	Hydrogen storage		
Household heating demand	Gas boiler	heatpumps		

Figure 20: Display of supply technologies implemented in the model to meet the different demand types, own representation

Electricity demand can be covered with wind power plants, photovoltaic, and CHPs using biomethane and waste. To balance electricity supply from fluctuating renewables, Lithium-Ion batteries can be used. Commercial and industrial heat can be supplied by combined heat and power plants, which produce electricity and heat simultaneously, as well as by excess heat from electrolyzers. This implies that these plants have to be installed close to industrial sites with heating demands, as transporting heat requires a heating grid and is only economically feasible for short distances. In addition, commercial and industrial heating demands can be met with heat pumps and boilers burning biogas. Cooking demand has to be covered directly in the households or commercial sites with either biogas or electric stoves. In the transport sector, it is assumed that vehicles are either using electricity directly in battery-electric cars or converting hydrogen to electricity in hydrogen-electric cars. The drive train is electric in both vehicle concepts. Hydrogen is produced out of electricity via electrolyzers. Household heating demand can be met with gas boilers using biomethane or heat pumps. CHPs and electrolyzers cannot supply household heating demand, as this would require a heating grid, which is not seen as an economically viable option.

5.2 Variation of energy demand

For all demand sectors, two different demand projections have been constructed as input for the scenarios. The base scenario is the one that is described in chapter 4.1. In a second scenario the demand in all sectors is increased by 30 %.

5.3 Variation of fuel price

While costs for technologies change rather slowly and can usually be predicted quite well based on economy of scale, fuel costs are dependent on many boundary conditions like available resources, current production capacities, demand for the fuel in different parts of the world, and therefore political and economic developments in all countries using that fuel, etc. As the scenarios show options for 100 % RE, the energy system is independent from fossil fuels like gas and coal, and only biomass is used. Biomass is not traded internationally or even nationally, but is used locally. This makes prices easier to predict. Still, the price for collecting waste and manure is not known and especially for the collection of chicken manure it has already been discussed with the local government that a reconstruction of the stables is necessary. This could increase collection costs. Therefore, three different prices for biomethane have been calculated and used in different scenarios.

5.4 Variation of wind power share on electricity supply

In the least cost scenario (see 6.2) wind power share is 40 %. From the local government, solar power is seen as the more realistic option for providing electricity because of shorter planning processes and better scalability. In addition, wind power is not easy to depict in a model like KomMod, as good wind power sites are dependent on many factors that cannot be incorporated in a model, like local wind speed, possible threats to birds or other species etc. For these reasons, different shares of wind power are set in different scenarios to show different possible energy systems based on how much wind power can be realized in Avellaneda. The shares are set to 0 % and 20 %. In addition, the optimal share of 40 % is a result in the least cost scenario where no shares for technologies are set in the model, but the least cost energy system structure is calculated.

5.5 Business-as-usual scenario

Total system costs are one of the results from energy system modeling (see chapter 3) including all costs for investment, operation and maintenance, fuels, and potential costs for carbon dioxide emissions. But there are also many cost types not included in such a stylized energy system model, such as network charges, grid expansion costs, or profits for energy providers. Energy transport in the model is ideal and therefore loss-free which leads to an underestimation of installable capacities of power plants. Because of this, the total costs of different scenarios can be used to compare them with each other but are not suitable to compare them to “real” total costs of an energy system. Because of that, a business-as-usual scenario is calculated where the energy supply in 2050 is constructed according to one scenario from (Beljansky et al. 2018). For the BAU scenario in this study the FEP scenario has been chosen which can be rated in comparison to the other scenario as rather ambitious with 79 % RE on electricity supply. The reason to choose an ambitious scenario as BAU scenario is that the scenarios in (Beljansky et al. 2018) are only projected until the year 2040. Further RE deployment in the years 2040-2050 can be expected and should be incorporated by choosing an ambitious scenario for the year 2040 as business as usual scenario for 2050. (Beljansky et al. 2018) only projects electricity supply structure but does not give any information on transport or heating sector. For the transport sector, data from (Aliano et al. 2019) is used. This data source is also used to project the number of vehicles through 2050. In addition, it projects the number of electric vehicles in the two vehicle categories buses and cars. For cars a share of 37.2 % electric vehicles is projected in the ambitious scenario and for buses a 100 % share of electric vehicles is projected. The share for cars is set for all other types besides buses. Energy demand for cooking and heating is not fixed in the business-as-usual scenario but can be covered with all available technologies. It is further assumed that gas used from the gas grid is 50 % biomethane and 50 % natural gas. The shares of different technologies and fuels in the BAU scenario are summarized in Table 12

Table 12: Share of different energy supply technologies in the business-as-usual scenario for 2050

	Cooking and heating	**Electricity (adapted from (Beljansky et al. 2018)**	**Transportation (own assumptions and information from Aliano et al. (2019)**
Hydro Power		14.2 %	
Photovoltaics		17.8 %	
Wind Power		45.8 %	
Gas power plants		5.5 %	
Oil power plants		2.4 %	
Biogas CHPs		14.1 %	
Diesel/Gasoline			Buses: 0 % All other vehicles: 62.8 %
Electric			Buses: 100 % All other vehicles: 37.2 %
Remarks	Optimized in model, same technologies as in 100 % RE scenarios but gas from gas grid is assumed to be 50 % biomethane and 50 % natural gas		

5.6 Overview

Table 13 gives an overview of all scenarios that have been calculated and are presented in this report.

Table 13: Overview over all calculated scenarios

Scenario name	Fuel price (low, mean, high)	Demand (base, high)	Wind power share on electricity supply
Leading scenario	mean	base	20 %
Least-costs scenario	mean	base	free
No wind power	mean	base	0 %
High demand	mean	high	20 %
High fuel price	high	base	20 %
Low fuel price	low	base	20 %
Business-as-usual	mean	base	According to (Beljansky et al. 2018)

The group of scenarios is constructed around the leading scenario, which has been agreed on by relevant stakeholders during the workshop where the pre-final scenarios have been presented. The leading scenario is the first one in Table 13.

6 Results

6.1 Leading scenario: mean demand, mean fuel price, 20 % wind power on electricity supply

From the six different scenarios that have been calculated (see Table 13), one has been chosen as the leading scenario. This is the scenario with mean demand, mean fuel price and a fixed share of electricity supply provided by wind of 20 %. In the least cost scenario (see 6.2), wind power share is 40 %. From the local government's perspective, solar power is seen as the more realistic option for providing electricity because of shorter planning processes and better scalability. In addition, wind power is not easy to depict in a model like KomMod, as good wind power sites are dependent on many factors that cannot be incorporated, like local wind speed, possible threats to birds or other species etc. Because of that it is seen more realistic that wind power is not the technology with the highest share on power supply but PV.
This leading scenario will be presented in detail in chapter 6.1.1. A detailed discussion of the operation of the different power plants during the year is done in chapter 6.1.2. In chapter 6.2 a comparison of all calculated scenarios is conducted. Chapter 6.3 presents a transition plan from today until 2050 to reach the leading scenario, while in chapter 6.4 a risk analysis is performed, linked with recommendations for overcoming the most common risks when transitioning to 100 % RE.

6.1.1 Energy supply

Figure 21 shows how electricity demand is covered by the different technologies in the leading scenario. The total electricity demand in this scenario that has to be covered is 420.4 GWh. This electricity demand consists of the electricity demand in the different sectors, as well as demand in the transport sector for vehicles using electricity directly and hydrogen, cooking demand that is covered with electric stoves, and electrification of heating demand in the commercial and industrial sector. The largest electricity supplier is photovoltaic with 61 %; of this, free field photovoltaic has the largest share with 53 %. The second-largest supplier is wind power, whose share is restricted in this scenario to exactly 20 %. Biomethane CHP follows closely with 19 %.

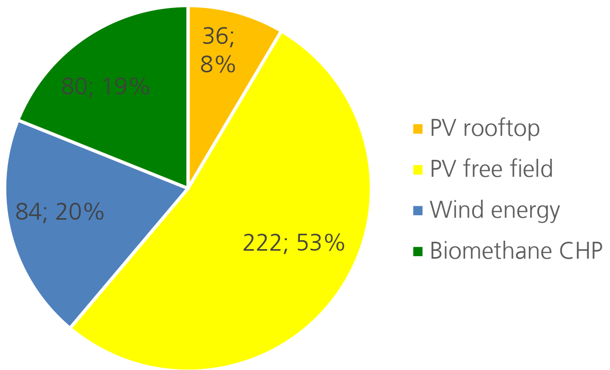


Figure 21: Results for the leading scenario for electricity supply in 2050 in GWh

Some of the implemented technologies in the model for electricity production are not installed in this scenario; these are waste CHPs and fuel cells. The levelized costs of energy for waste CHPs are shown in Figure 38, and, as they are higher than the levelized costs of energy for biomethane CHPs, they would only be installed if the potential for biogas from manure is already fully used. Fuel cells use hydrogen and convert fuel energy back to electricity and heat. This process is associated with losses, but has the advantage that storing hydrogen has better efficiency, especially in the long term, than storing electricity in batteries. But in the presented scenarios, batteries are used as a storage option, because short-term storage is sufficient to balance supply and demand, therefore making batteries the cheaper option.

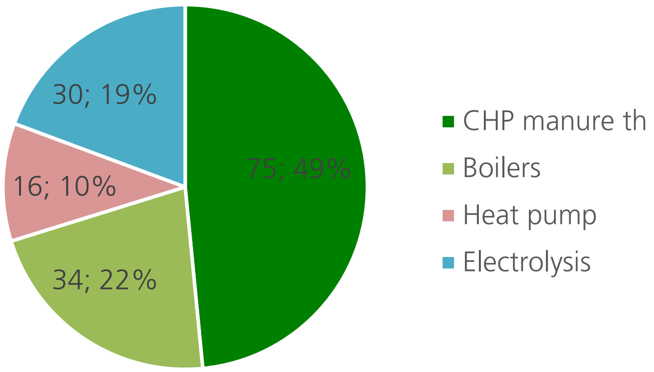


Figure 22: Results for the leading scenario for heating supply in 2050 in GWh

Heating demand over all sectors is 155 GWh. The heating demand is met with four different kinds of supply technologies (Figure 22). The largest share comes from the combined heat and power plants with 49 %, the second largest share is coming from boiklers with 22 %, excess heat from electrolyzers accounts for 19 %. The smallest portion of 10 % is covered by heat pumps. It should be noted that the usage of CHPs and electrolyzers to cover heating demand implies that heating demand is located close to these supply technologies. As already described above, waste CHPs are not installed due to higher costs than biomethane CHP. In addition, also biomethane-burning boilers are not used.
Cooking demand is mainly met with stoves using biomethane with 93 % share. Electric cooking accounts for the remaining 7 %. (Figure 23).

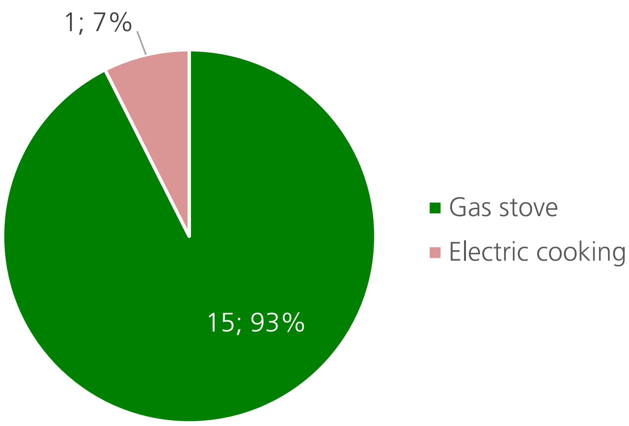


Figure 23: Results for the leading scenario for energy for cooking supply for 2050 in GWh

Figure 24 shows the energy flow (Sankey) diagram for the leading scenario. On the left-hand side are the different power plant types that are used in the leading scenario and produce electricity or heat. On the right-hand side, the different energy demand types are presented. This energy flow diagram distinguishes between energy for cooking demand, commercial and household heating demand, electricity demand, energy demand in the transport sector, and industrial heating demand. Electricity supply adds up to 421 GWh including electricity demand in the transport sector, for appliances in the different sectors, in transport, for heating purposes, as well as for the production of hydrogen, which is presented in the middle of the energy flow diagram. Hydrogen is used in the transport sector. Heat pumps are depicted in the upper middle part of the diagram and supply heat to households. They take heat from the environment, for example out of the air or ground and, by compressing the gaseous working fluid, the temperature of this fluid is increased and heat can be used for space heating or warm water supply. Not all losses are shown in this picture, only the ones from electrolysis, battery storage and electric cooking. The power plant processes shown in the left of the figure also have losses when converting fuel energy into electricity and heat, but for the sake of simplicity these have been left out.

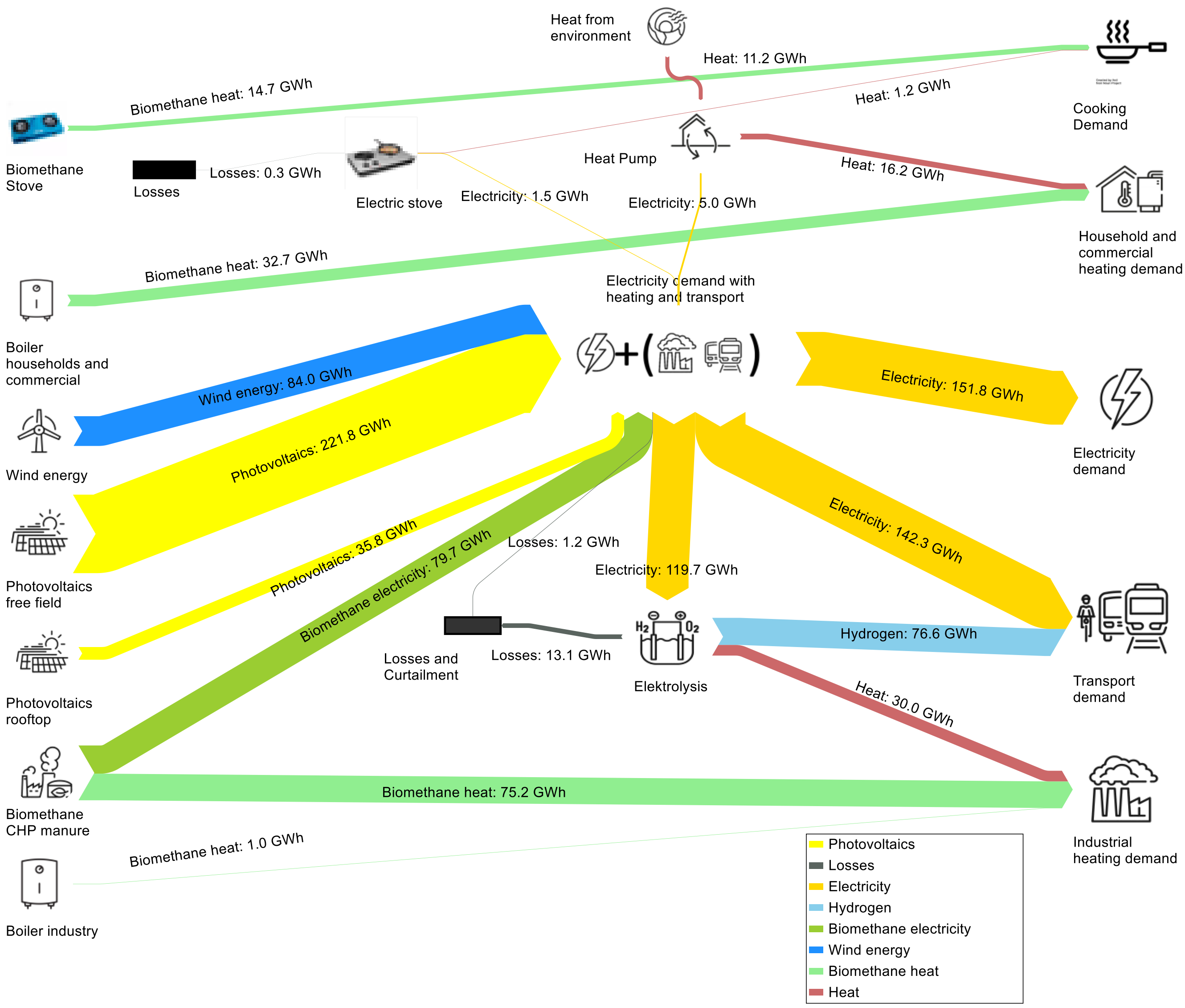


Figure 24: Energy Flow diagram of the leading scenario

The largest installed capacity of all supply technologies is PV free-field (see Figure 25). This is the supply technology with the largest amount of supplied energy and, at the same time, the lowest full load hours of around 1300 h-1400 h per year. Batteries are also installed to a high extent (342.8 MWh), as the majority of electricity supply is coming from fluctuating resources (PV and Wind). Thermal storages (hot water storages) are used to store heat from CHPs, electrolyzers, and heat pumps for later use. They are installed at a capacity of 0.72 MWh.

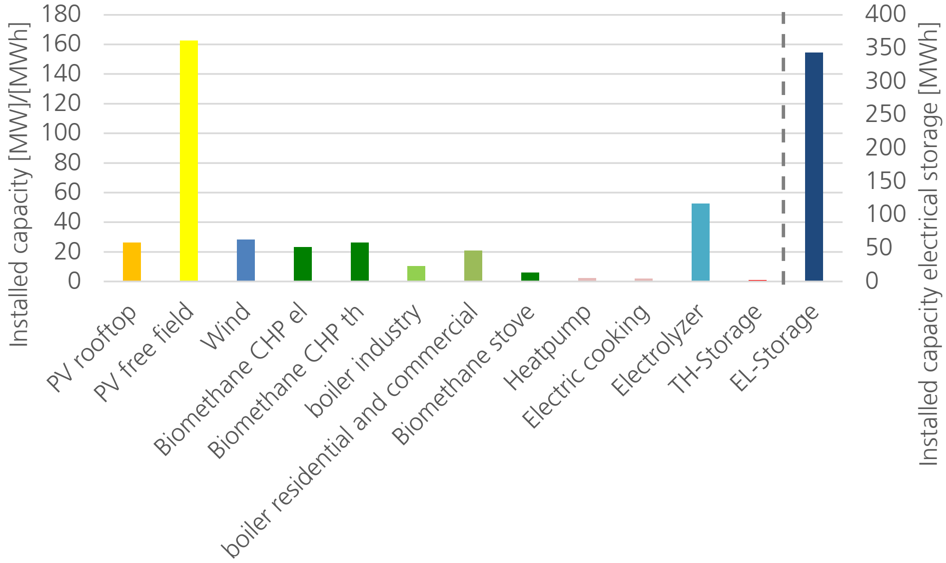


Figure 25: Installed capacities of all installed technologies in the leading scenario

6.1.2 Time series evaluation

An assessment of the temporally resolved results of the scenarios helps to understand how the different power plants are operating throughout the year and how storage technologies help to balance power generation from fluctuating renewable technologies. Figure 26 shows power generation and demand for one week in June 2050 for the leading scenario (the figure is to be found in a higher resolution in Appendix D). Demand is shown with lines, with a red line indicating net demand (demand given to the model exogenously) and a blue line indicating gross demand (demand calculated during optimization including electricity for heating, cooking and hydrogen production). CHPs (in green) run at night, when no output from photovoltaic power plants is available. PV (in yellow) reaches its maximum output in the shown week on June 27 at around 1 pm with 104 MW. This is higher than the gross demand, and excess electricity is stored for use in times when no electricity from solar is produced. There is one peak in the evening from charging electric vehicles (at 7 pm) which is at least partly covered every evening with electricity from batteries. Gross demand is especially high when lots of electricity output from PV is available; this electricity is used in electrolyzers to produce hydrogen for the transport sector and reduces battery needs. Wind energy output is high in the shown week; notable amounts of electricity from wind are produced, especially at night, and are a good supplement to solar electricity, which is only produced in the daytime.
High excess electricity output from solar PV could cause challenges for the future electricity grid, if this excess electricity were fed into the grid all at once. One option to reduce network load could be the decentral installation of battery storages. Especially on large free field photovoltaic power plants, battery storages can be built up next to the plant, allowing electricity to be stored directly and fed into the grid in the evening hours when it is needed. It is also an option for rooftop PV systems that households

own their own battery storage in addition to the PV systems and store excess electricity by themselves for later use. As KomMod does not model any networks, no quantification of grid load can be given here, but this should be part of a more detailed planning process for grid expansion, as the share of PV power plants in the electricity system of Avellaneda rises in the future.

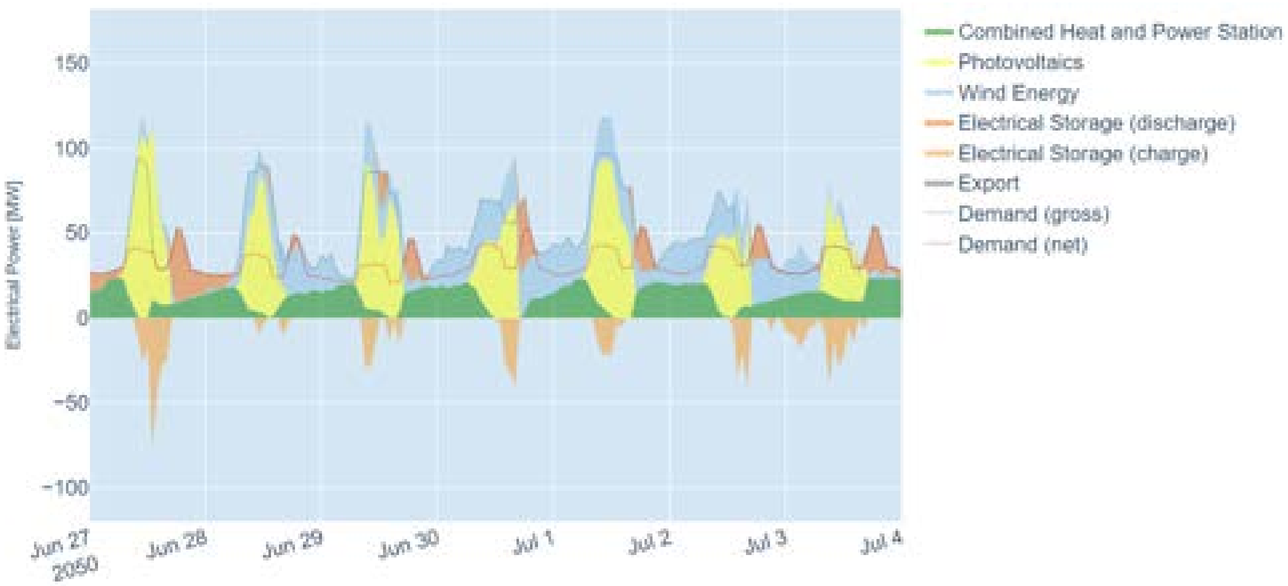


Figure 26: Time series for one week in June for electricity supply and demand for the leading scenario

Figure 27 shows in contrast a week with nearly no electricity supply from wind power but high electricity output from solar PV. In this week PV produces up to 167 MW electricity output. Parts of it are stored in batteries and used in the night, but another part is being exported.

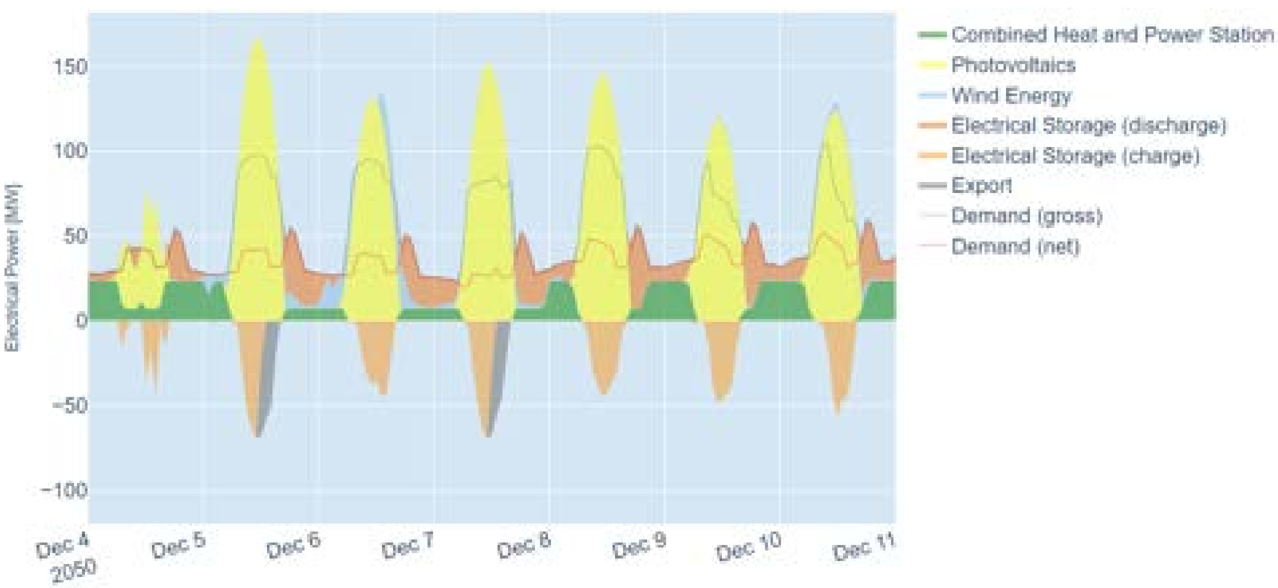


Figure 27: Time series for one week in December for electricity supply and demand for the leading scenario

Figure 28 shows the supply and demand of heat in the industry sector. The red line shows the demand, which is covered with two different technologies: CHPs, which simultaneously supply heat and electricity (see Figure 26), and electrolyzers, which supply heat at times when no heat output from CHPs is available. As electrolyzers are running mostly when electricity from solar PV is available while CHPs are running mostly when no electricity from solar PV is available, the two technologies supplement each other well. But both technologies could produce even more heat than is needed, and a part of the heat output is therefore curtailed.

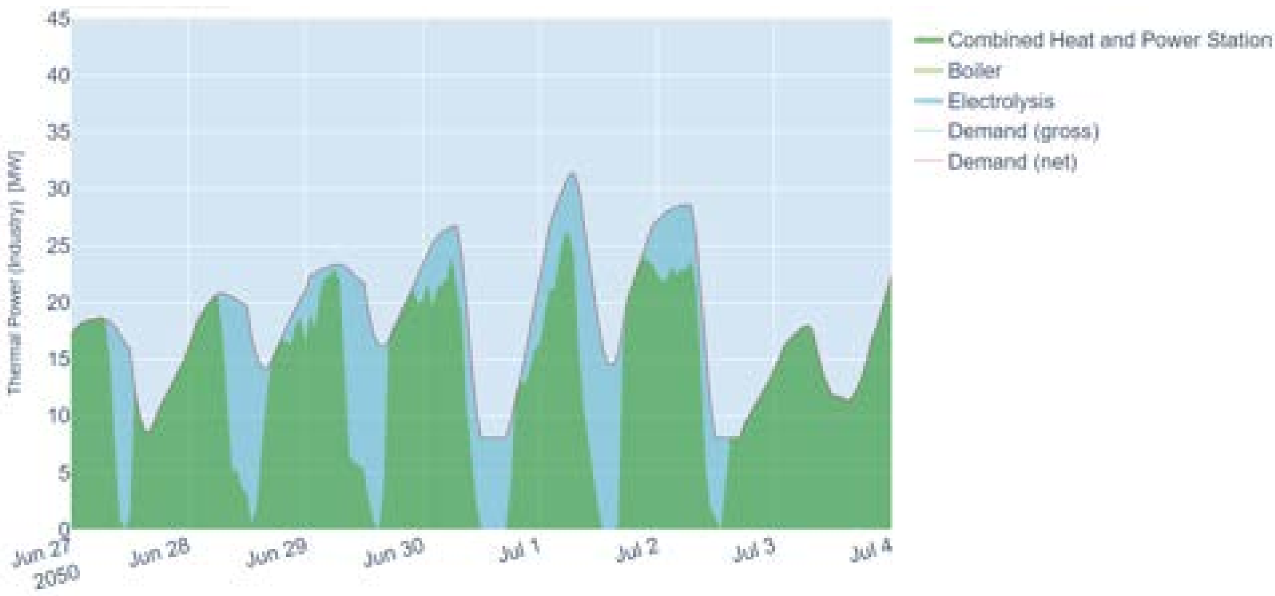


Figure 28: Time series for one week in June for heating supply and demand in industry sector in the leading scenario

Heating demand in households and industry sector is mainly covered by boilers using biomethane (see Figure 29). Figure 29 also displays the stylized way decentral heating supply is depicted in the model. In the real world, every household and commercial enterprise has a heating technology installed in their building, and, as buildings are not connected via heating grid, heat cannot be exchanged in between buildings. As it is assumed that all households and commercial enterprises have the same heating demand and the heating demand per household and commercial entity is scaled up to get the total heating demand, all heating supply technologies should always have the same share on total heat production, as every entity uses its own heating technology. In the model, any heating technology can cover any demand, because no spatial resolution is being predicted. This is visible in the figure, as there are times when heat pumps are not running but boilers cover the total heating demand at that times.

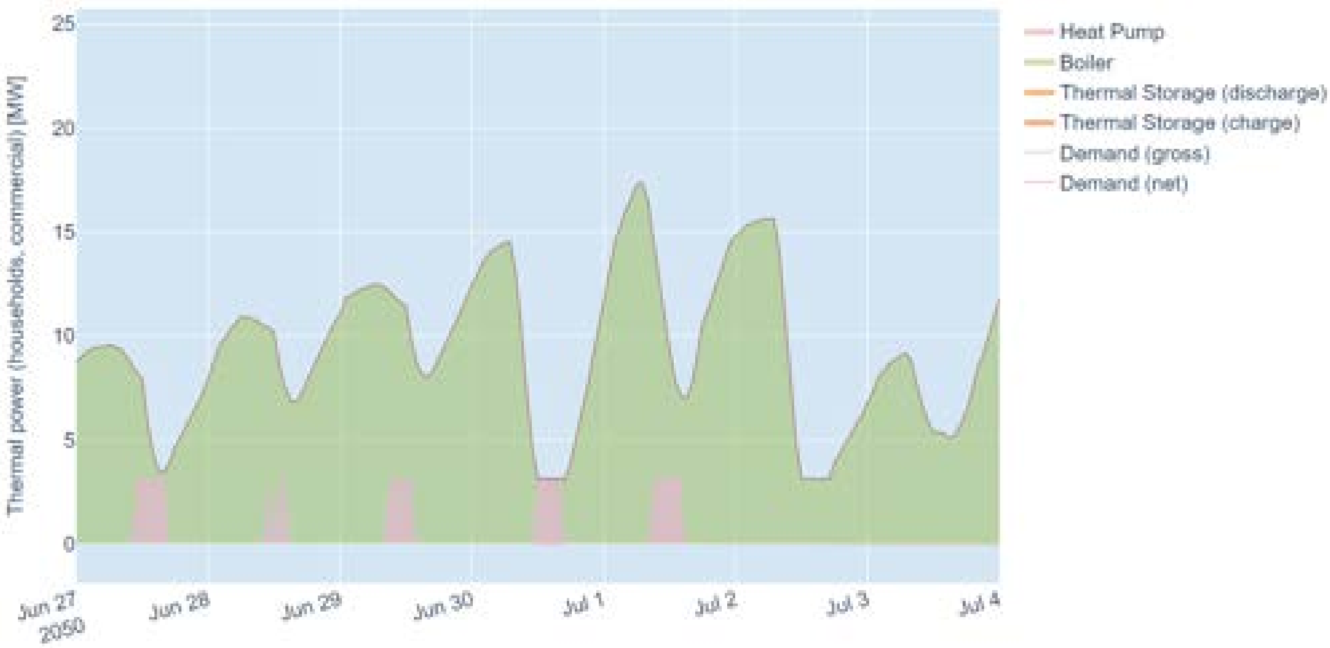


Figure 29: Time series for one week in June for heating supply and demand in household and commercial sector in the leading scenario

Over the whole year, cooking demand is met 93 % by biomethane stoves and 7 % by with electric stoves. As can be seen in Figure 30, the installed capacity of biomethane stoves is high enough to meet the peak in cooking demand of nearly 8 MW. Still, electric stoves are used instead of electric cookers at certain times. This operation, like heating supply, shows the results of stylized modeling, which cannot always depict real-world behaviour of (in this case) single households. In the real world every household has one cooking device and will always use that one, so some entities (household/commercial) will always use electric stoves instead of biomethane stoves. In the model, there is one cooking demand time series, and all installed cooking devices can cover this demand, so there are times when biomethane stoves meet the entire demand.

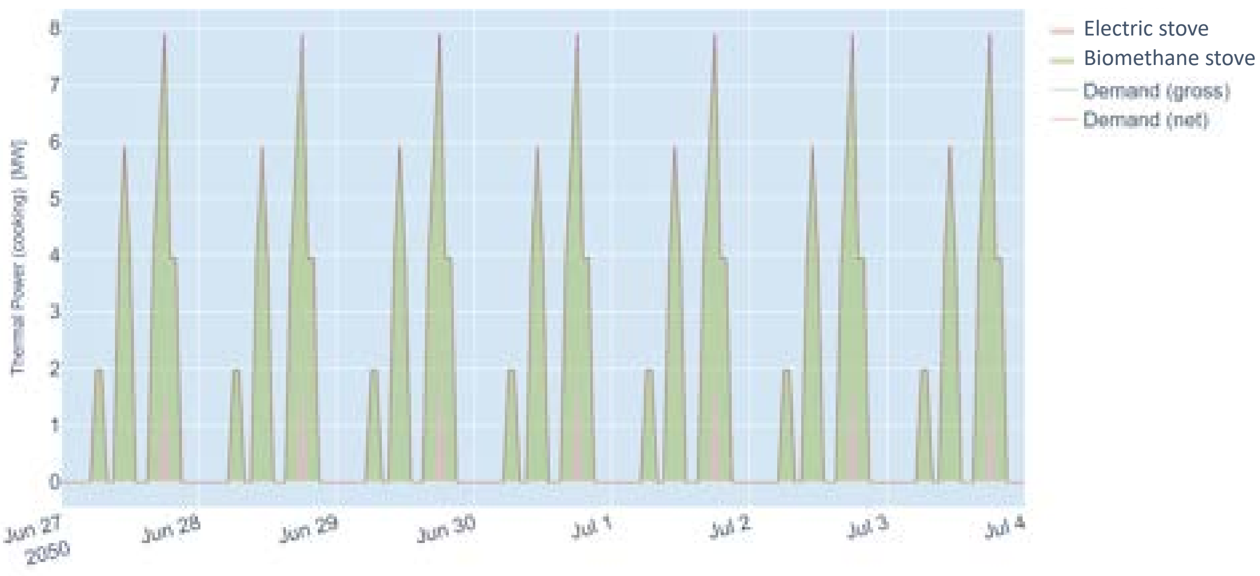


Figure 30: Time series for one week in June for cooking supply and demand for the coupled scenario with mean demand and high fuel price

Figure 31 depicts the same week in June for the scenario with no wind power installed. Output from PV is neatly 1.5 times higher (see Figure 26), so excess electricity and stored electricity which has to be used at night, when no output from PV is available. Electrolyzers use excess electricity during the day and are not running at night (see blue demand line).

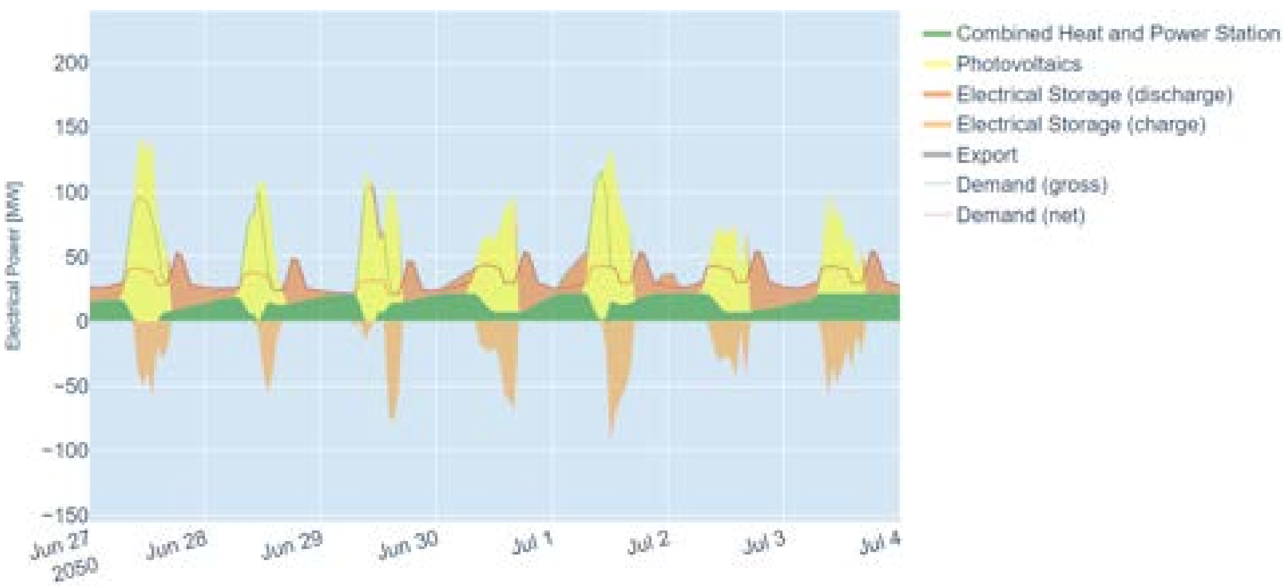


Figure 31: Time series for one week in June for electricity supply and demand for the scenario with no wind power installed

The quite opposite case is shown in Figure 32 in the least cost scenario, where 40 % of all electricity is supplied by wind power plants. In the shown week, wind power supplies the largest part of electricity production and hydrogen production is high when output from wind power plants is high, even at night. In weeks with little output from wind power less hydrogen is produced.

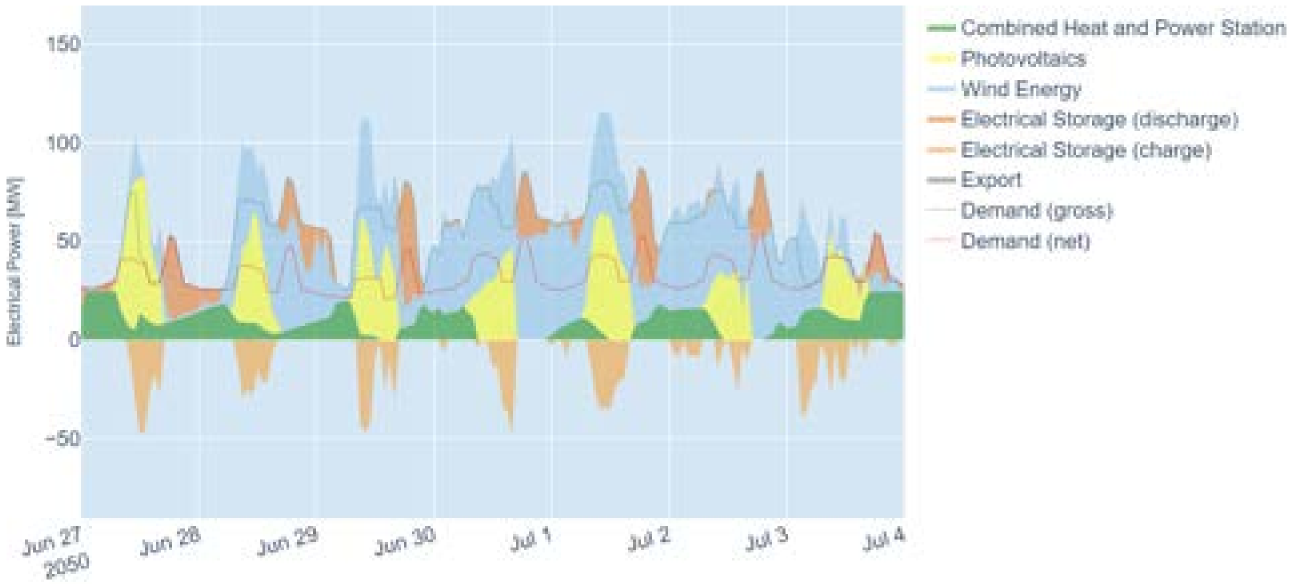


Figure 32: Time series for one week in June for electricity supply and demand for the scenario with 40 % wind installed (least cost scenario)

6.2 Comparison of all scenarios

Overall, 7 scenarios have been calculated. All results in table format can be found in Appendix C. In Figure 33, the electricity supply in all scenarios is shown. The least-costs scenario shows an energy system constructed only in regard to costs, where technologies are only restricted by their given potentials but not by any further restrictions. In the least-costs scenario, wind covers 40 % of the electricity supply, while PV supplies a share of 42 %. In the base scenario, as well as in the high fuel price, low fuel price, and high demand scenario, wind share is restricted to 20 %. This leads to PV being the major electricity supply technology, with shares of 24 % (low fuel price) to 73 % (high fuel price). In the no wind scenario, PV has the highest share, as no wind power plants are installed and PV replaces wind, leading to a share of 81 %. Influence of fuel price is clearly visible, as with high fuel price the share of biomethane CHPs decreases from 19 % in the base scenario to 7 %, while in the low fuel price scenario the share of biomethane CHPs increases to 61 %. Potentials for PV as well as biomethane are much higher than demand, and no boundaries for the potential are reached in any of the scenarios. The business-as-usual scenario has a much lower share of PV, with only 18 %, while wind power is the main contributor with 46 %. Fossil fuels (oil and natural gas) still cover 8 %. Electricity demand is lower than in the other scenarios as less electricity is needed for the transport sector which is still mainly dependent on fossil fuels in the business-as-usual scenario.

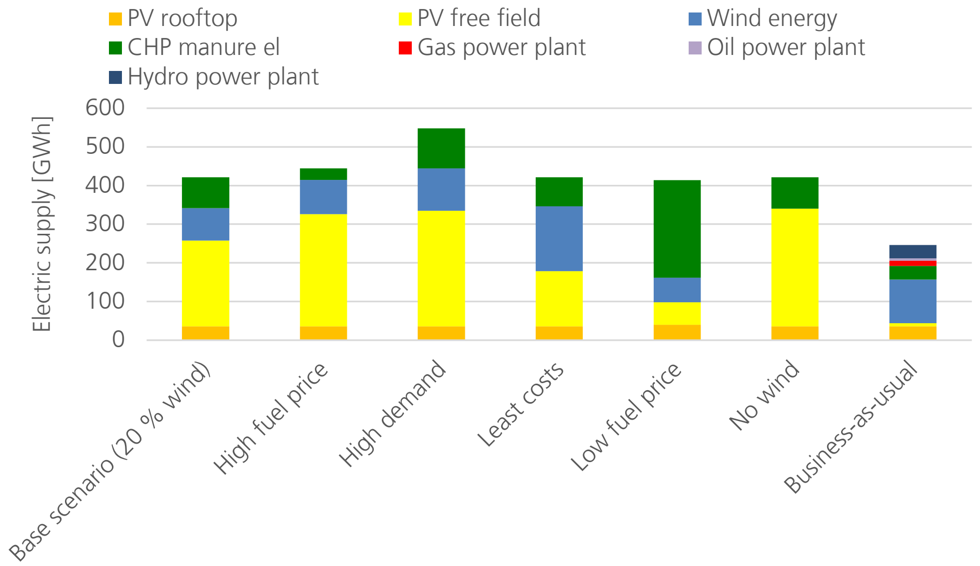


Figure 33: Comparison of electricity supply in all scenarios

The supply of heat is depicted in Figure 34. Four different technologies supply heat to cover household, commercial, and industrial heating demand. In the graph no distinction is made, but CHPs and electrolyzers can only cover industrial heating demand as the heat from these plants can only be used when industrial sites are close to them. As no heating grid is installed in Avellaneda, it is assumed that this is only possible for industrial sites.

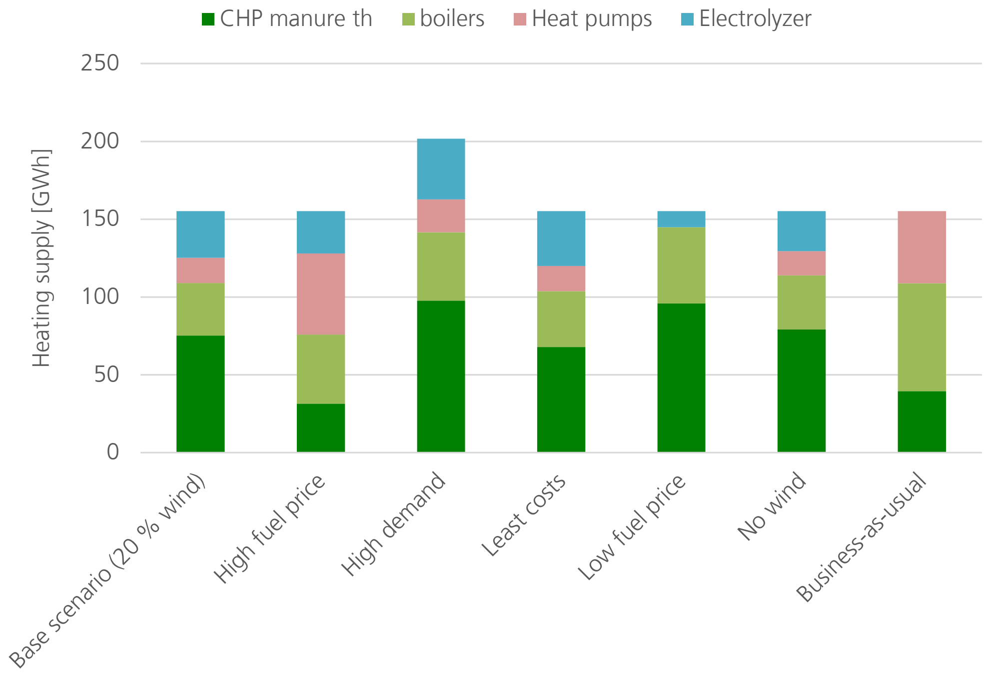


Figure 34: Comparison of heating supply in all scenarios

Boilers and heat pumps can be used in all sectors. Hydrogen demand is the same in all demand scenarios except high demand and business-as-usual. In the high demand scenario hydrogen demand is higher, while in business-as-usual scenario there is no hydrogen demand as vehicles use either electricity or mainly fossil fuels. The share of

heat supply provided by electrolyzers varies between 7 % and 23 %, because heat is partly curtailed depending on the heat output from CHPs, as more heat from CHPs and electrolyzers is available in some scenarios than needed (for example in low fuel price scenario). With low fuel price, no heat pumps are used, as it is cheaper to use biomethane in CHPs and boilers. Heat pumps have the highest share in the high fuel price scenario where the use of biogas is more expensive (see also Figure 34). Also, in the business-as-usual scenario, heat pumps are used to a higher extent, as no electrolyzers are installed and therefore no excess heat from electrolysis can be used.
Energy for cooking demand (see Figure 35) is mainly covered with biomethane stoves in all scenarios, with the share varying from 56 % to 100 %. The highest share is reached in the low fuel price scenario, while the lowest share is reached in the high fuel price scenario. The shares of biomethane stoves with different shares of wind on electricity supply vary only at a small extent between 5 % and 11 % with higher shares of biomethane stoves when less wind energy is used.

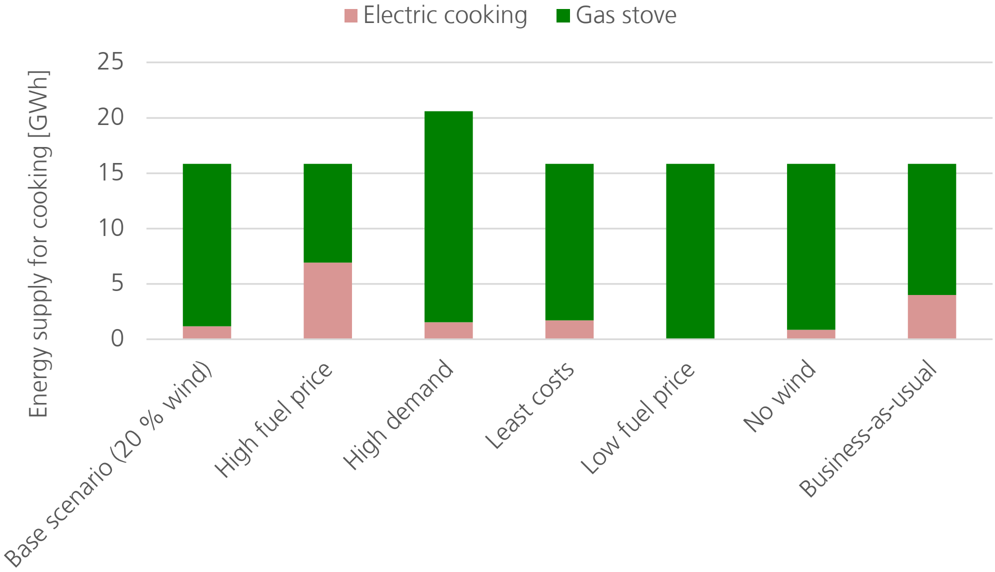


Figure 35: Comparison of cooking supply in all scenarios

Figure 36 shows the range of full load hours of all technologies in all scenarios. Three technologies are only used in the business-as-usual scenario and are shown separately. As PV and wind power full load are dependent on solar irradiation and wind speed they are constant in all scenarios. The full load hours of CHPs vary between 1495 hours and 4597 hours. The lowest full load hours occur in the high fuel price scenario, where CHPs are used to cover demand in times when electricity from wind and PV is not available. Highest full load hours occur in the low fuel price scenario, where the share of biomethane CHPs is much higher and they run as base load power plants. Industry boilers have the highest full load hours in the high fuel price scenario, as less heat from CHP is available to cover heating demand, while in all other scenarios they serve as a peak load heat supply technology. Highest full load hours are reached by heat pumps, which serve mainly household heating demand with full load hours because of assumed constant demand for domestic hot water. The full load hours of electrolyzers are higher in scenarios with higher shares of biomethane CHPs because of more constant electricity supply. In scenarios with higher shares of PV, electricity supply fluctuates more, so hydrogen production of electrolyzers is lower (see also Chapter 6.1.2).

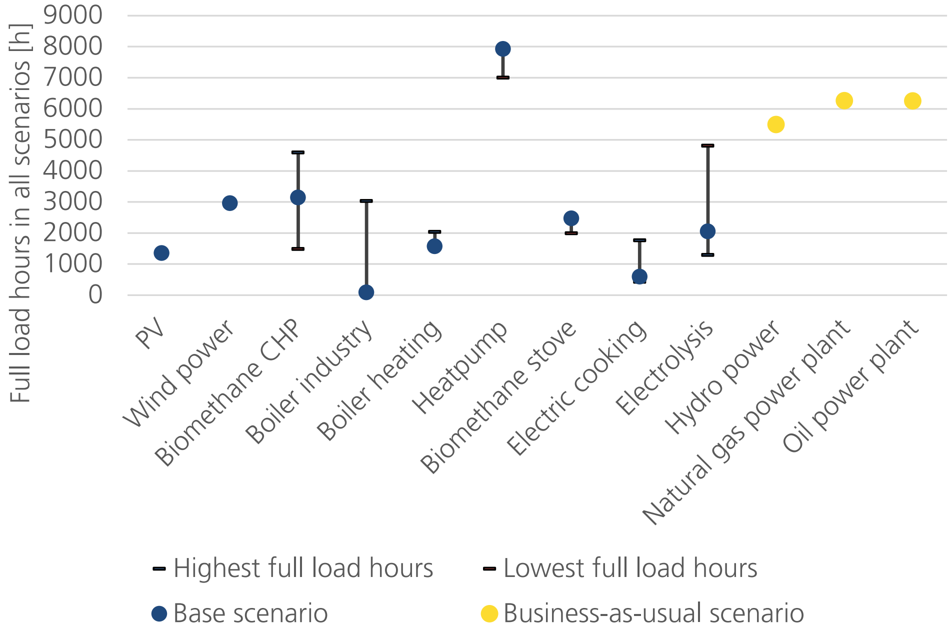


Figure 36: Full load hours of all technologies in all scenarios

100 percent RE can be reached in all calculated scenarios even with high demand scenarios. An assessment of the used potentials helps to understand whether 100 percent RE would still be possible, if demand were even higher in the future. Figure 37 depicts the potentials of rooftop PV, free field areas used for wind and PV, and biomethane.

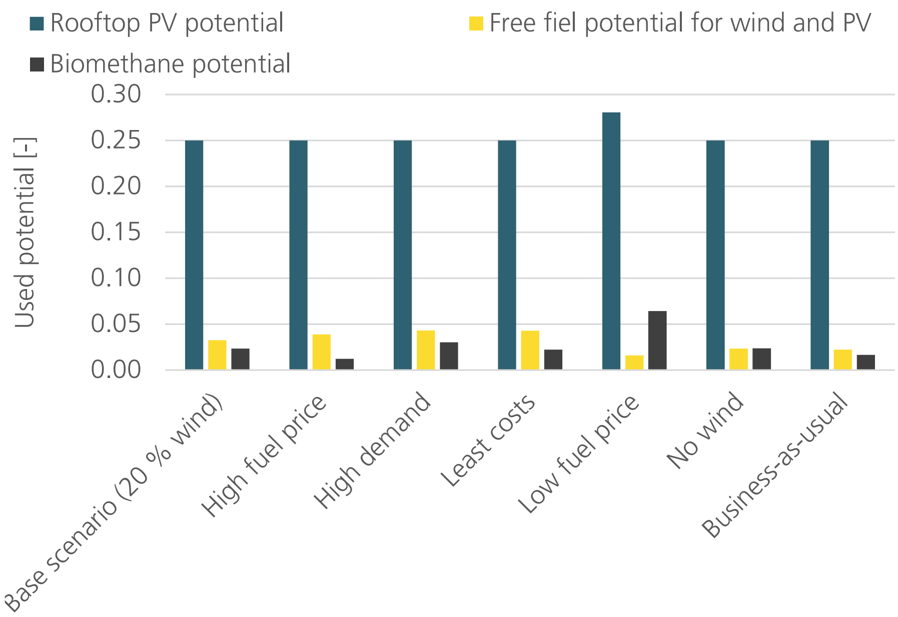


Figure 37: Used potentials PV and Wind in all 100 % RE scenarios normalized to the maximum potential

The usage cannot be compared between the different types of RE, as overall potentials differ a lot from each other (see Figure 16). Rooftop potential is 25 % utilized in most of the scenarios, as all potential in the cardinal direction of north is used but not in the

other directions, where full load hours are a little bit less, as angle is not that optimal. Small shares of free field areas for PV and wind as well as biomethane potentials are used in all scenarios. Free field area is used between 1.6 and 4.3 %. In the high demand and high fuel price scenarios most PV and wind power plants are installed, while in low fuel price scenario the potentials are used least. The trends are the opposite for the usage of biomethane, except for high demand, where overall more energy has to be supplied to cover higher demand.
Table 14 depicts the used free field area for PV and wind power, and the relative size of the used area compared to the total area of Avellaneda in all scenarios, with values between 0.2 % and 0.55 %. The percentage of the theoretical maximum biomethane production is shown in the same table, varying from 1.23 % to 6.44 %. Overall, it can be summarized that Avellaneda has very high potentials for renewable energy generation compared to its energy demand, leading to a minor usage of these potentials. This leads to a great freedom of choice as to which technologies should be used in a future 100 % renewable energy system. The cost optimal solution is highly dependent on costs, such as the manure price (and therefore also price for biomethane). This can be seen in Figure 33 where, in the low fuel price scenario, the share of biomethane CHPs is very high, while in the high fuel price scenario it is low and PV takes a larger share on electricity supply. Due to considerations of supply security, it is always beneficial to diversify between the different technologies; this was a factor in the choice of the leading scenario in this study.

Table 14: Land use of wind power plants, free field PV and rooftop PV in all scenarios

Scenario	**Used free field area for Wind and PV [km²]**	**Share on overall area Avellaneda [%]**	**Biomethane amount used [GWh]**	**Share on biomethane amount [%]**
Base scenario (20 % wind)	3.89	0.42 %	256.2	2.33 %
High fuel price	4.62	0.49 %	135.4	1.23 %
High demand	5.15	0.55 %	333.0	3.04 %
Least-costs	5.10	0.54 %	245.8	2.24 %
Low fuel price	1.90	0.20 %	706.3	6.44 %
No wind	2.79	0.30 %	261.1	2.38 %
Business-as-usual	2.65	0.28 %	180.6	1.65 %

Figure 38 depicts the modelled levelized costs of electricity (LCOE) and heat (LCOH) of all technologies. They describe the costs to produce one kilowatt-hour of electricity or heat with a certain technology. PV is the technology with the lowest LCOE at 0.03 €/kWh (3.51 ARS/kWh). When the costs for installing batteries are added, the LCOE increases to 0.039 €/kWh (4.485 ARS/kWh). The total costs for batteries are added to the total costs for PV and wind power and the new LCOE is calculated accordingly. LCOE for wind power is 0.04 €/kWh (4.6 ARS/kWh) without battery costs and 0.049 €/kWh (5.6 ARS/kWh) with battery costs included. LCOE for biomethane CHPs varies between 0.027 €/kWh (3.1 ARS/kWh) in the low fuel price scenario and 0.09 €/kWh (10.4 ARS/kWh) in the high fuel price scenario. Electric stoves are more expensive than biomethane stoves when costs for electricity are added; this is the reason why biomethane stoves have much higher shares in nearly all scenarios. Industrial boilers have the same capital and fuel costs as boilers used in households, higher LCOH due to lower full load hours as boilers in the industry sector are used to cover peak loads while boilers in the household sector are used at higher full load hours.

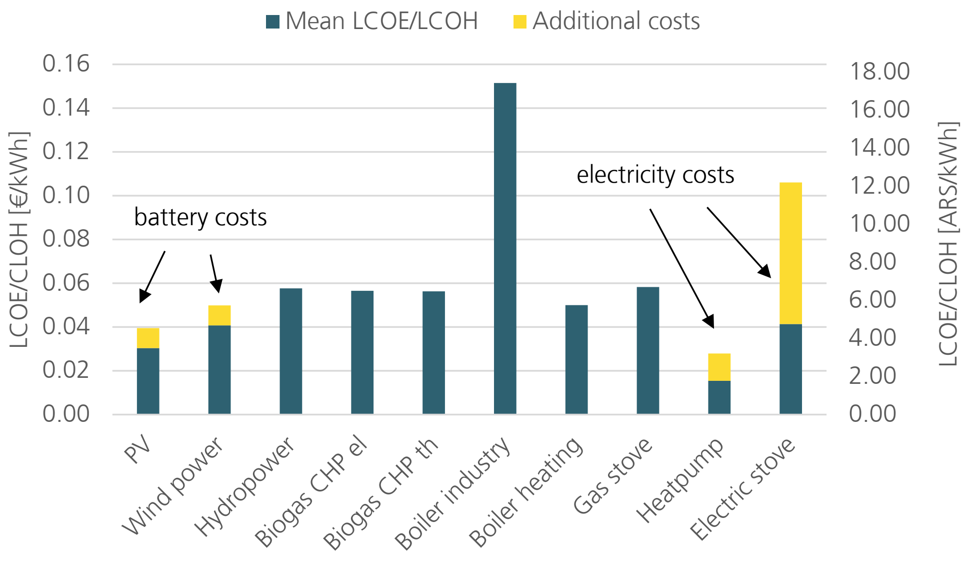


Figure 38: Levelized costs of electricity and heat for all technologies, mean value for all scenarios

Figure 39 shows the overall system costs in all scenarios normalized to the costs of the leading scenario. The least-costs scenario is 2.7 % cheaper (which uses 40 % of wind energy). Increasing the fuel price by 50 % leads to a 12 % higher energy system costs, as well as less biomethane usage. If the fuel costs are decreased by 50 %, the energy system is 22 % cheaper and biomethane is used to a much higher extent. In the high demand scenario, the demand is 30 % higher, resulting in a 30 % more expensive energy system. The business-as-usual scenario is the most expensive, with 54 % higher system costs than the base scenario. These higher costs are attributable mainly to the usage of fossil fuels in the transport sector and partly to the use of more expensive electricity supply technologies than in the 100 % RE scenarios.

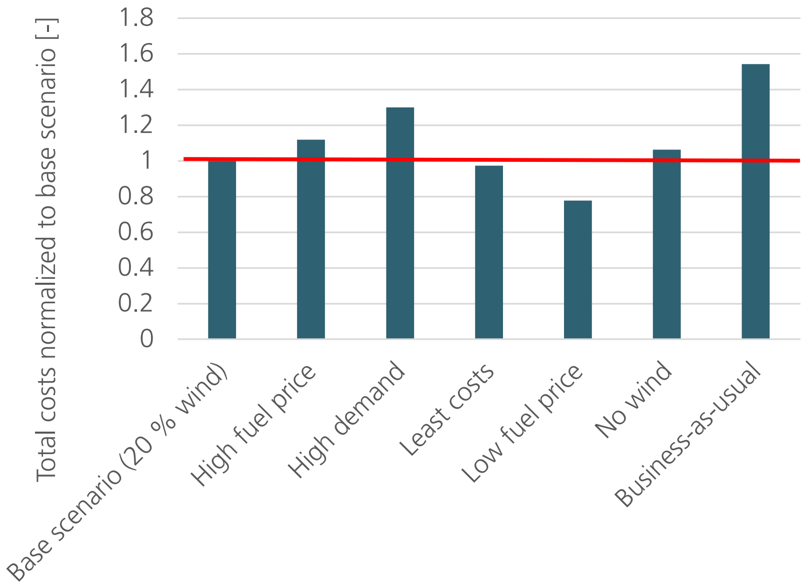


Figure 39: Total system costs in all scenarios normalized

The direct CO_2e emissions in all scenarios are depicted in Figure 40. Direct CO_2e emissions include only emissions from burning fuel; no carbon dioxide equivalents from the production of different power plants are included. This leads to the result that CO_2e emissions are higher in the lower fuel price scenario, where more biogas is used. Biogas has lower CO_2e emissions than, for example, natural gas, but due to transport of biomass, leakage in the biogas production process, etc. they are not zero. The direct CO_2e emissions from burning fuels are 3.5 times higher in the business-as-usual scenario than in the leading RE scenario, but only 27 % higher than in the low fuel price scenario. It should be noted that one of the most ambitious scenarios from the scenario family presented in (Beljansky et al. 2018) has been chosen, and with all other business-as-usual scenarios CO_2e emissions would be even higher (see Chapter 5.5 for more information).

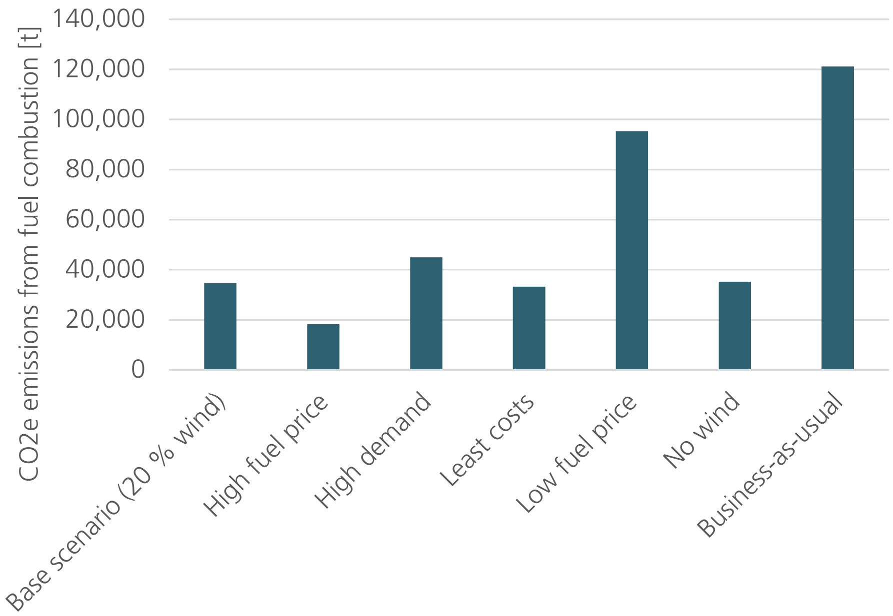


Figure 40: Direct CO_2e emissions in all scenarios

6.3 Transition Plan

The elaboration of a detailed transition plan will be part of the ongoing project, but some first insights into possible transformation pathways of Avellaneda’s energy system shall be already given here. It is considered as very important that the right investment decisions are made from now on, which means that ideally no new investments in fossil technologies shall be made, as these investments would eventually be stranded. This means that private households should also be incentivized to invest into renewable energy technologies like biogas stoves and PV power plants.

Figure 41 shows one possible pathway for electricity generation to reach the leading scenario in the year 2050. Today the share of local renewable electricity generation is small, with one biogas power plant beginning its operation. The rest of the electricity demand is covered with imports. These imports are mainly coming from fossil fueled power plants, but share of renewables in the Argentinian power system is increasing.

As electricity demand is projected to rise by 4 times by 2050 in the mean demand scenario (including electricity demand for fuels, heating and transport demand), new power plant capacities have to be installed quite soon to cover growing electricity demand in Avellaneda or other parts of Argentina. As photovoltaic is an easily scalable and decentral technology, it is recommended to start the expansion very soon. Biogas CHPs can also be installed in the next two to three years as soon as biogas production plants have been built up. Manure from livestock is available in large amounts and biogas CHPs can therefore directly fossil fuel power plants. Wind power plants need longer planning processes, as suitable locations must be found by analyzing wind speed, potential risks for certain birds and other threats to nature. These processes should be started, now that the commissioning of first wind parks is realistic by around 2026. As it can be seen in Figure 41 electricity demand is rising quite slow until 2030, from that year on increase is steeper as electricity demand for transport sector and the production of hydrogen is also rising more and more.

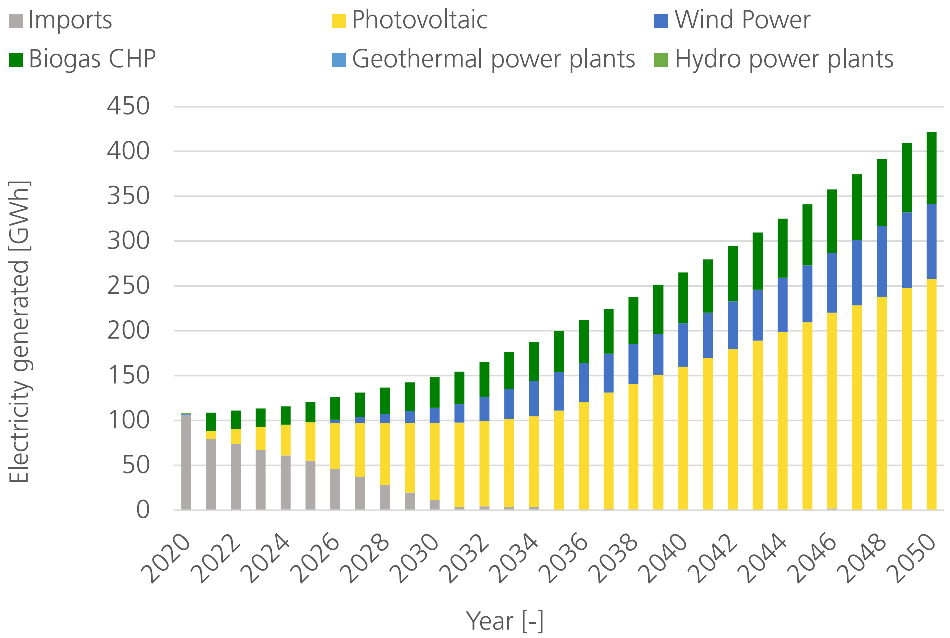


Figure 41: Generated electricity in the years 2020-2050 in the leading scenario

Figure 42 shows the share of overall fuel usage of different fuels in transport sector up to 2050, aggregated for all vehicle types. Today it is assumed that the transport sector is fully dependent on fuel-combustion engines, although the first electric vehicles may already be in use in Avellaneda. The first vehicles that are assumed to be electrified are motorcycles. Especially for smaller motorcycles traveling short distances, the technology is mature and easily available already today. For electric cars their deployment is seen as realistic from the year 2025 on, but share is increasing slowly at the beginning. Hydrogen vehicles are seen as realistic only from the year 2032 onwards, as today not many different manufacturers produce hydrogen buses and trucks and prices are still high. Simultaneously with the adoption of the new vehicles, charging and refueling infrastructure must be installed.

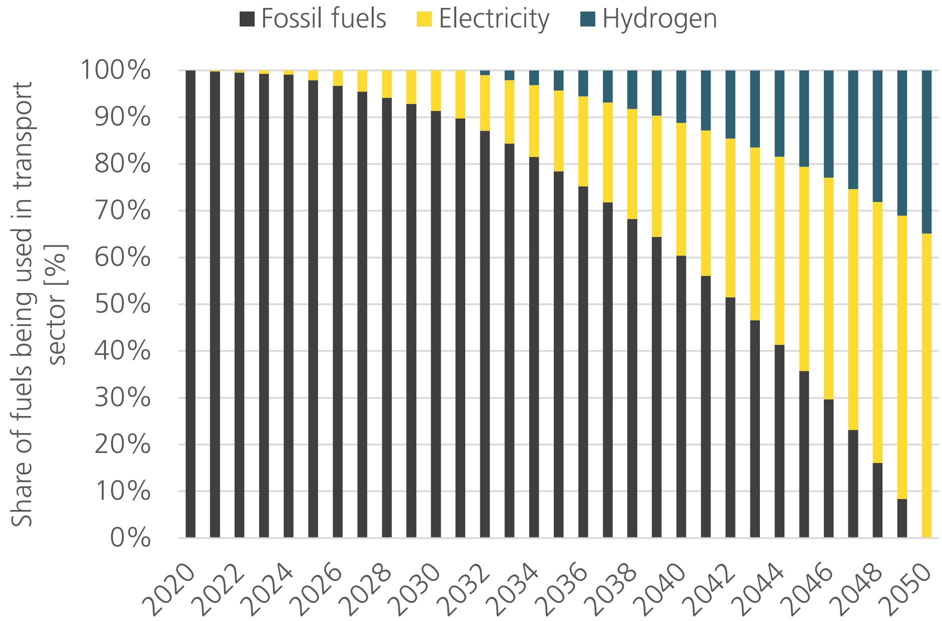


Figure 42: Share of different drive train concepts over all vehicle types in the leading scenario from today until 2050

Figure 43 depicts the expansion of heating supply technologies in commercial and industry sector as well as in households. CHPs, electrolyzers as well as boilers industry are covering heating demand in industry sector as it is assumed for CHPs and electrolzers that heat is produced close to industrial site where it can be directly used, while households and smaller commercial enterprises cannot use excess heat from CHPs and electrolyzers as no heating grid is and will be installed in Avellaneda. In households and small commercial enterprises, boilers and heat pumps cover heating demand which are directly installed onsite.

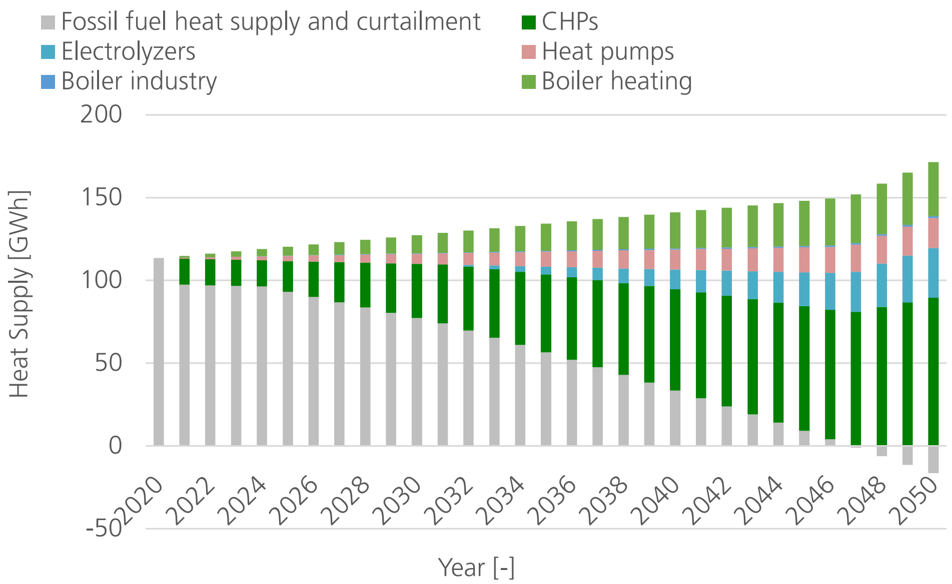


Figure 43: Share of different heat supply technologies on overall heat supply in the leading scenario from today until 2050

Fossil fuels for covering heating demand are still in use for quite a long time, as heat for industry demand comes from CHPs and electrolyzers. Electrolyzers are only available from 2032 onwards, and biogas CHP capacity is expanded according to rising electricity demand. But it would also be possible to expand biogas CHPs earlier to have more heat available to cover industrial heating demand. As boilers using natural gas are most likely used today, it is also possible to use biomethane produced out of manure much earlier in boilers and replace them eventually when heat from biogas CHPs is available. The same holds true for covering heating demand in households, as it is assumed that biomethane will be produced, which can simply be fed into the gas grid or be admixed with natural gas for as long as production is lower than demand. As biogas is processed to biomethane to have the same quality as natural gas, the natural gas boilers can be used with biomethane and no new devices must be bought by industrial and commercial facilities or households. From the year 2048 onwards, excess heat is produced by CHPs and electrolyzers at times where not all of this heat is needed in the industrial sector. This is depicted by negative heating supply in Figure 43.
Today's cooking technologies (mainly gas) shall be used with biomethane from the gas grid in the future as already described for usage of boilers in households. Therefore, it is not the case that one section of the household cooking demand will use stoves and boilers with biomethane and the other section of the demand will still use natural gas; rather, the share of biomethane in the gas grid will increase according to biomethane production in Avellaneda. In the leading scenario it is seen the best economic option for a small portion of households to use electric cooking (see Figure 44).

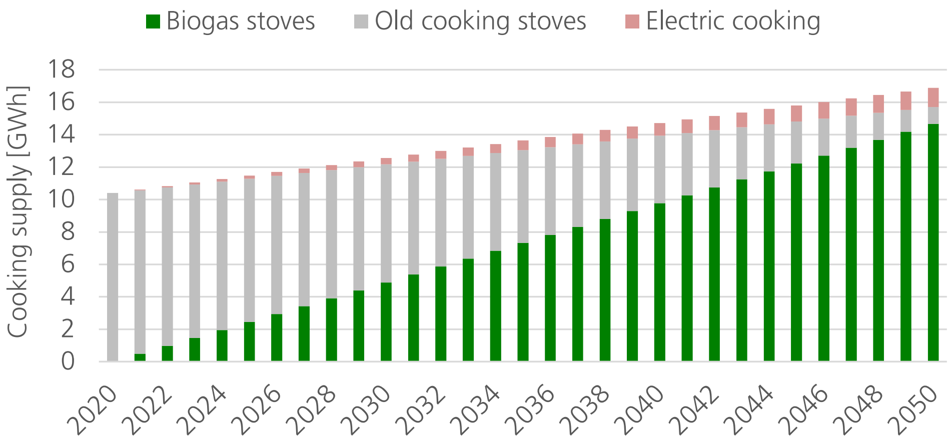


Figure 44: Share of biogas and old cooking stoves on overall cooking supply in the leading scenario from today until 2050

6.4 Risk analysis and Recommendations

Electricity supply:

- Supply security is more difficult to ensure when fluctuating renewables take high shares on overall electricity production. In the model, supply security is ensured by modeling with a high time resolution and endogenous calculation of needed storage capacity. But nevertheless, the needed storage capacity is dependent on parameters like the availability of the installed storages and the longest period where little to no renewable energy from fluctuating renewables is produced because of low wind speed and low solar irradiation (so called "Dunkelflaute"). In the model, battery storages are implemented as storage technologies. Other storage options like compressed air reservoirs or hydrogen could be additional options for increasing supply security. Hydrogen will already be produced for the transport sector and could be used in fuel cells to produce electricity when needed as back up technology.

- PV deployment is high in all scenarios that have been calculated, and it is a technology that can easily be scaled up. The promotion of the installation of PV power plants is therefore recommended. Prices are already quite low today, but subsidies could help to make the installation of PV even more attractive, also for households and commercial enterprises.
- Especially for wind power plants, a detailed assessment of possible sites is inevitable. It is recommended to conduct feasibility studies including detailed measurements of wind speeds in the near future to determine the best locations and start the planning process. To ensure a successful process and the detection of the most suitable sites, as well as a high acceptance of the technology, all stakeholders should be included in the planning process like people living nearby, environmental organizations who know about potential threads for birds nesting close to the potential sites, the local electricity supply company, the grid operator, and the local government.
- Less energy demand in the future directly leads to a less expensive energy system, as fewer power plant capacities have to be installed and less fuel is needed. Projections of energy demand show that demand will most probably increase in the future. There are several reasons for this, such as growing welfare, and therefore the use of more appliances in the household as well as in the commercial sector. Efficient appliances can be promoted or even subsidized, as well as a thoughtful usage thereof.
- Fossil fuel power plants should not be expanded in Avellaneda, as these will eventually become stranded assets. Electricity demand will increase in the future, and additional demand should be covered directly with renewable technologies.
- Avellaneda isn't an island, and at the present electricity is mainly imported from other parts of Argentina where power plants are installed. In this project, the aim was to determine how much of Avellaneda's energy demand can be covered with local resources. Still, it might be beneficial to work together with other provinces that could have better potentials for some technologies and where installation is more feasible than in Avellaneda. Electricity can then be imported at certain times. This could for example be the case for wind power plants, as wind speed might be higher in other parts of Argentina. But what should not be forgotten is that, as long as Argentina's energy supply is not fully based on renewables (see BAU scenario), importing electricity always means importing non-renewable electricity.
- Increasing electricity demand, as well as expansion of PV and wind power in the rural parts of Avellaneda, will make grid expansion necessary to prevent congestion, and has to be part of future planning processes for power plant expansion.

Transport sector:

- As Avellaneda's vehicles are not only driving in the province of Avellaneda but to other provinces or even neighbouring countries, they also must have the possibility of being charged somewhere else. A solely local solution in the transport sector is therefore not possible. This means that in the transport sector nationwide solutions have to be found. Charging infrastructure must be in place before electric vehicles driving longer distances can be widely put to use. Therefore, the transport sector is seen as the sector in which achieving 100 % RE is fraught with the most risks.

- One vehicle type that can be used already today and is not dependent on vast charging infrastructure are electric motorcycles, as they usually drive short distances.
- One important question to be solved regards the availability of electric and hydrogen cars in Argentina and their price. Today electric and hydrogen cars are more expensive than fossil fuel driven cars and many countries have subsidies to increase their market diffusion.
- The used projection for the development of energy demand in transport sector has the underlying assumption that the ownership of individual motor vehicles will increase in the next 30 years. Expansion of public transport as well as car sharing options can be solutions restrict energy demand increase in the transport sector.
- The use of hydrogen in trucks and buses can be seen seen as critical, as hydrogen cars are not widely available now, and the assumption that 50 % of all trucks are hydrogen vehicles in Avellaneda in 2050 may not be realistic. The other option would be to electrify trucks and buses fully. Whether this is realistic, due to the distances driven with these vehicles types, is still being discussed. But here, too, it is certain that a very good charging infrastructure will have to be in place if buses and trucks are to be 100 % electric in 2050.
- Using biofuels or synthetic fuels in Avellaneda in the transport sector could be another option, but has not been examined further in this study. There are high potentials of manure to produce fuels; these fuels can even be admixed with gasoline during a transition period to 100 % RE, which makes it possible to use existing vehicles.

Heating supply in industrial sector

- Heating purposes in industrial sector are diverse and highly dependent on the specific processes that are being conducted. Before deciding which is the best heating supply option for the different facilities their needs have to be understood and the possibility for an individual consultation has to be given for the companies to find tailor made solutions based on renewable energies for each company. Consulting programs for industrial facilities about energy saving measures and usage of renewable energies can be implemented for that purpose.
- The usage of excess heat from electrolyzers and CHPs relies on spatial proximity; therefore, it is recommended to build up CHP power plants and electrolyzers close to commercial and industrial sites.

Biomethane production

- Biomethane production should soon start to be admixed in the gas grid and used in CHPs to produce electricity and heat.
- To produce biogas, manure must be collected and brought to the biogas production facilities. It is beneficial if manure must only be transported for short distances as the calorific value is low before the biogas production process and transport costs should be kept at a minimum to keep biogas price low. The best locations for biogas production have to be found by taking into account the location of farms, as well as the locations of the gas grid and CHPs plants which should be located close to commercial and industrial sites because of the usage of heat

7 Conclusions

This study is able to show that, under the used boundary conditions, 100 percent renewable energy for Avellaneda is possible for the following sectors: electricity, heating, cooking and transport on land. The most important findings of the study are:

- 100 percent renewable energy is possible in all demand scenarios. Potentials for PV free field, wind power, and biomethane from manure are only used to a small extent (under 7 % each over all scenarios). This means that there is a high flexibility as to which RE technologies shall be used in the future and decisions can be based on other parameters apart from costs and availability, like acceptance or national and local policies.
- The leading scenario depicts an energy system where three different technologies are used with meaningful shares: biomethane CHPs, wind power plants and PV. PV has by far the largest share with 61 %, while wind power plants and biomethane CHPs cover around 20 %.
- In the least-costs scenario, wind power has a much higher share of 40 %. But as the local government sees solar power as the more realistic option for providing electricity because of shorter planning processes and better scalability, wind power share has been fixed to 20 % in the leading scenario. CHP share is highly dependent on the achievable costs for biomethane and in addition on the possibility of collecting manure at reasonable effort and cost.
- Varying the biogas fuel price to that extent that it is done in the scenarios leads to differences in energy supply. With low fuel price, biomethane CHPs provide 19 % of electricity supply, while with high fuel price it decreases to 7 %. In addition, with high fuel price the share of heat pumps to cover heating demand and the share of electric stoves to cover cooking demand increases.
- The business-as-usual scenario represents an energy system with lower ambitions for RE deployment, especially in the transport sector. While electricity supply comes 92 % from renewables, only 38 % of all vehicles drive electric, while the rest is still using fossil fuels. This scenario is 54 % more expensive and CO2e emissions are 3.5 times higher than in the leading scenario.

Recommendations and risks for the transition of the energy system of Avellaneda to 100 % renewables are described in chapter 6.4, the most important of which are:

- PV deployment is high in all scenarios that have been calculated and it is a technology that can easily be scaled up. The promotion of the installation of PV power plants is therefore recommended. Prices are already quite low today, but subsidies could help to make the installation of PV even more attractive, also for households and commercial enterprises.
- For wind power plants, a detailed assessment of possible sites is inevitable. It is recommended to conduct feasibility studies including detailed measurements of wind speeds in the near future to determine the best locations and start the planning process. To ensure a successful process and the detection of the most suitable sites, as well as a high acceptance of the technology, all stakeholders should be included in the planning process.
- As Avellaneda's vehicles drive not only in the province of Avellaneda but to other provinces or even neighboring countries, they must have the possibility to be charged somewhere else. A solely local solution in the transport sector is therefore not possible. This means that in the transport sector, nationwide solutions must be found. Charging infrastructure must be in place before electric vehicles driving longer distances can be widely applied. Therefore, the

transport sector is seen as the sector in which achieving 100 % RE is fraught with the most risks.

8 APPENDIX

A. Table of end energy demands today and in 2050

	Energy demand today	Base scenario 2050	High demand scenario 2050
All values in [GWh]			
Cooking residential	11.5	15.8	20.6
Heating residential (warm water and space heating)	19.8	27.4	35.6
Heating commercial (warm water, space heating, other purposes)	15.6	21.6	28.1
Heating industry (warm water, space heating, other purposes)	76.9	106.2	138
Electricity demand	103.2	151.8	197.4
Transport energy demand electric	0	142.3	185
Transport energy demand hydrogen	0	76.6	99.6
Transport energy demand fossil fuels	228	0	0
Sum	455.1	541.8	704.3

B. Specific energy demands of vehicles with different drive train concepts

	End energy consumption of fuel vehicle [kWh/100 km]	End energy consumption of electric vehicle [kWh/100 km]	End energy consumption of hydrogen vehicle [kWh/100 km]
Motorcycles	32 (Böke 2007)	4 (Böke 2007)	
Car	45 (Mauch 2009)	20 (Wikipedia 2021)	29 (Mauch 2009)
Bus and truck	291 (Schmied and Mottschall 2014)	115 (Bünnagel 2020)	300 (Kupferschmid and Faltenbacher 2019)

C. Energy supply and installed capacities of all technologies in all scenarios in 2050

Leading scenario

	Capacity [MW]	Generation [GWh]	Generation [t]	Full load hours [h]
PV rooftop	26.26	35.8		1364
PV free field	162.6	221.8		1364
Wind power	28.4	84.1		2963
CHP Biomethane el	23.26	79.7		3149
CHP Biomethane th	26.16	75.2		3149
CHP waste el				
CHP waste th				
Boiler industry	10.52	1		94.6
Boiler residential and commercial	20.8	32.7		1577
Heat pumps	2.29	16.2		7930
Stove biomethane	5.92	14.7		2477
Stove electric	1.97	1.2		602
Electrolysis	52.46	30	2301	2056
Electrical storage	342.8			
Thermal storage	0.72			

High fuel price

	Capacity [MW]	Generation [GWh]	Generation [t]	Full load hours [h]
PV rooftop	26.26	35.8		1364
PV free field	212.9	29		1364
Wind power	29.92	88.7		2964
CHP Biomethane el	19.28	29.7		1495
CHP Biomethane th	21.69	31.5		1495
CHP waste el				
CHP waste th				
Boiler industry	5.7	17.4		3039
Boiler residential and commercial	17	27		1593
Heat pumps	9.45	52		7190
Stove biomethane	3.95	8.9		2260
Stove electric	3.95	1.8		1766
Electrolysis	62.38	27.3	2301	1659
Electrical storage	555.7			
Thermal storage	22.21			

High demand

	Capacity [MW]	Generation [GWh]	Generation [t]	Full load hours [h]
PV rooftop	26.26	35.8		1364
PV free field	219.22	299		1364
Wind power	36.88	109.3		2963
CHP Biomethane el	30.23	103.6		3149
CHP Biomethane th	34.01	97.7		3149
CHP waste el				
CHP waste th				
Boiler industry	13.68	1.3		94.6
Boiler residential and commercial	26.99	42.6		1577
Heat pumps	2.97	21.1		7929
Stove biomethane	7.7	19.1		2477
Stove electric	2.57	1.5		602
Electrolysis	68.2	39	2991	2056
Electrical storage	445.7			
Thermal storage	0.93			

Least-costs

	Capacity [MW]	Generation [GWh]	Generation [t]	Full load hours [h]
PV rooftop	26.26	35.8		1364
PV free field	104.6	142.6		1364
Wind power	57.9	167.9		2898
CHP Biomethane el	24.6	74.8		2747
CHP Biomethane th	27.68	67.85		2747
CHP waste el				
CHP waste th				
Boiler industry	8.94	3.2		358.8
Boiler residential and commercial	20.73	32.7		1576
Heat pumps	2.31	16.3		7908
Stove biomethane	5.92	14.1		2388
Stove electric	1.97	1.7		871.5
Electrolysis	33.33	35.1	2301	3482
Electrical storage	297.7			
Thermal storage	1.44			

Low fuel price

	Capacity [MW]	Generation [GWh]	Generation [t]	Full load hours [h]
PV rooftop	29.48	40		1337
PV free field	42.79	58.4		1364
Wind power	20.88	63.28		3031
CHP Biomethane el	36.7	252.3		4597
CHP Biomethane th	41.3	95.9		4597
CHP waste el				
CHP waste th				
Boiler industry	0	0		0
Boiler residential and commercial	23.9	49		2046
Heat pumps	0	0		0
Stove biomethane	7.89	15.8		2007
Stove electric	0	0		0
Electrolysis	15.84	10.3	2301	4816
Electrical storage	78.51			
Thermal storage	0.72			

No wind

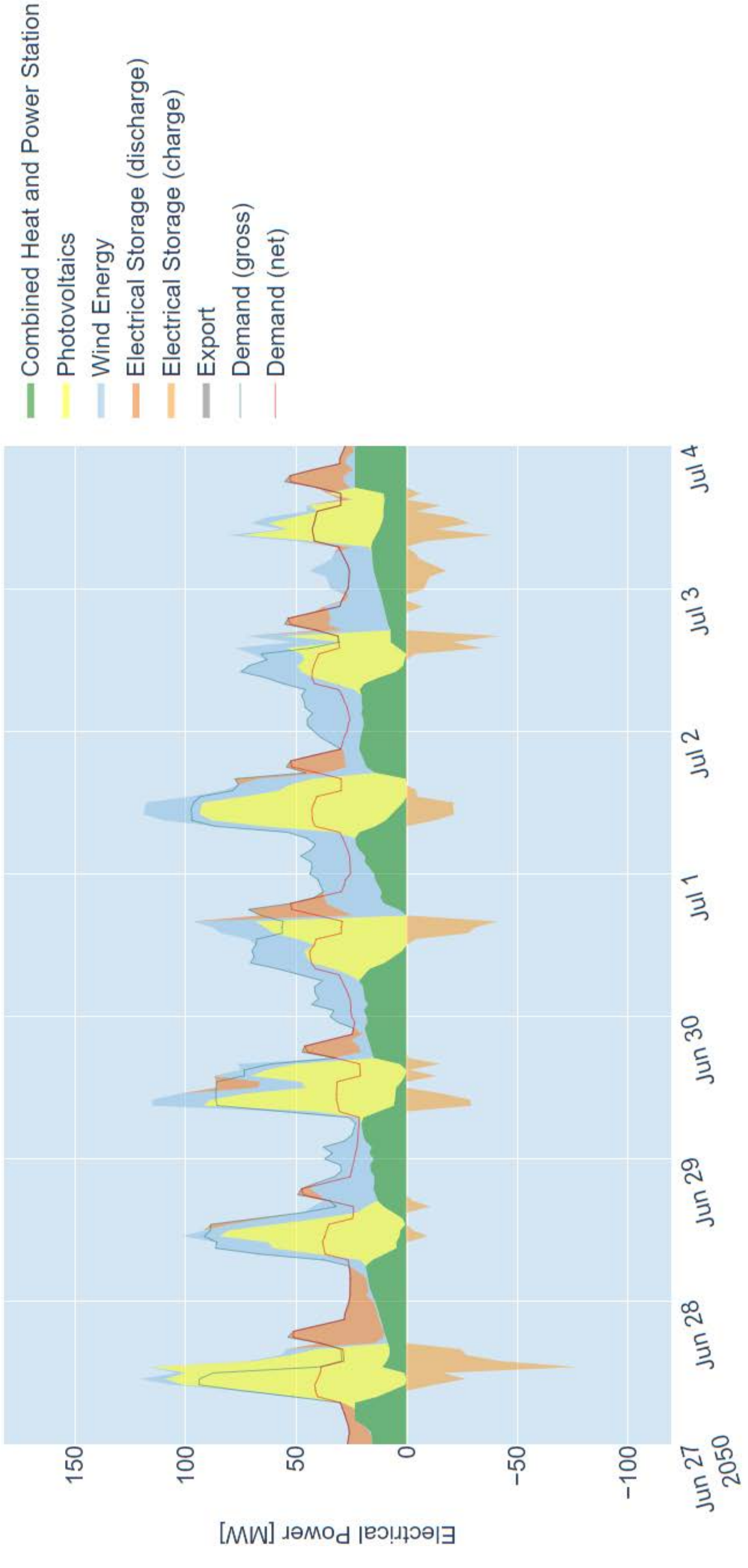
	Capacity [MW]	Generation [GWh]	Generation [t]	Full load hours [h]
PV rooftop	26.26	35.8		1364
PV free field	223.05	304.2		1364
Wind power	0	0		0
CHP Biomethane el	21.53	81		3514
CHP Biomethane th	24.23	79.1		3514
CHP waste el				
CHP waste th				
Boiler industry	10.84	1.3		124
Boiler residential and commercial	20.76	33.4		1607
Heat pumps	2.28	15.6		7484
Stove biomethane	5.92	15		2531
Stove electric	1.97	0.85		437.94
Electrolysis	77.83	25.7	2301	1297
Electrical storage	475.49			
Thermal storage	0.72			

Business-as-usual

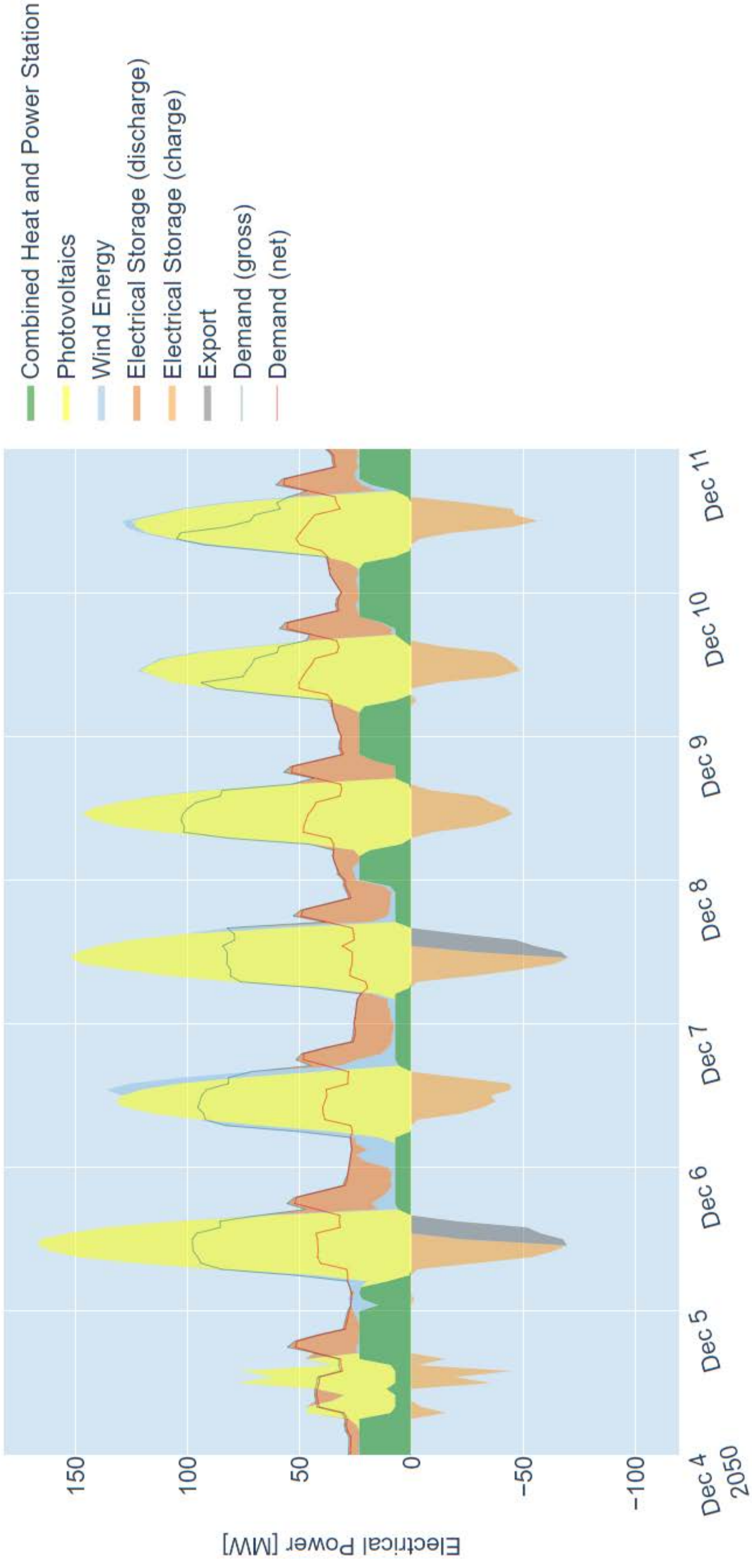
	Capacity [MW]	Generation [GWh]	Generation [t]	Full load hours [h]
PV rooftop	26.26	35.8		1364
PV free field	5.9	8.1		1364
Wind power	39.34	112.9		2869
Hydropower	6.36	35		5500
CHP Biomethane el	6.87	35.1		5103
CHP Biomethane th	7.73	39.5		5103
Gas power plant	2.17	13.6		6262
Oil power plant	0.96	6		6258
Boiler industry	26.29	38.6		1469
Boiler residential and commercial	19.47	30.8		1581
Heat pumps	8.66	46.3		7010
Stove biomethane	5.92	11.8		2001
Stove electric	3.95	4		1019
Electrolysis	0	0		0
Electrical storage	65.52			
Thermal storage	4.14			

D. Time series of leading scenario

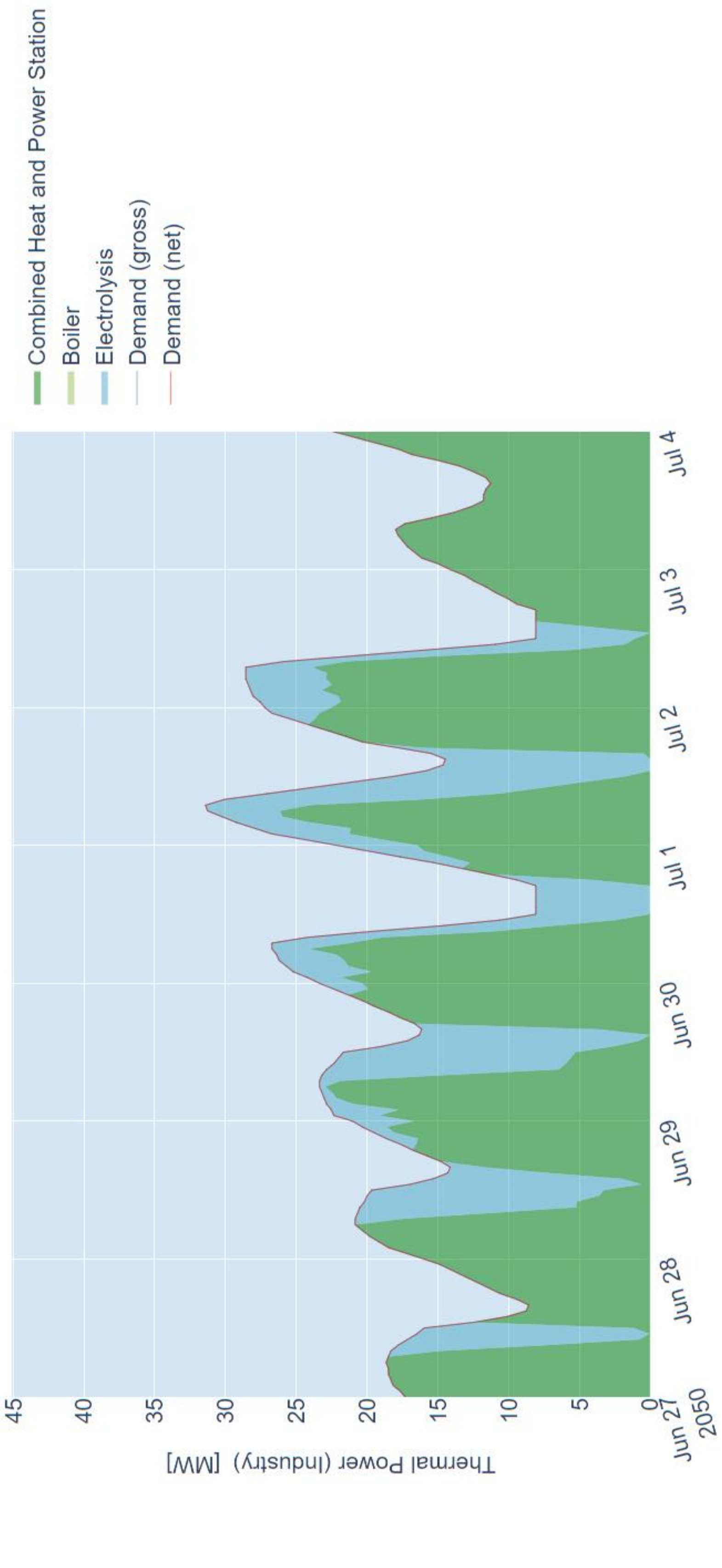
Leading scenario: One week in June, electricity supply and demand



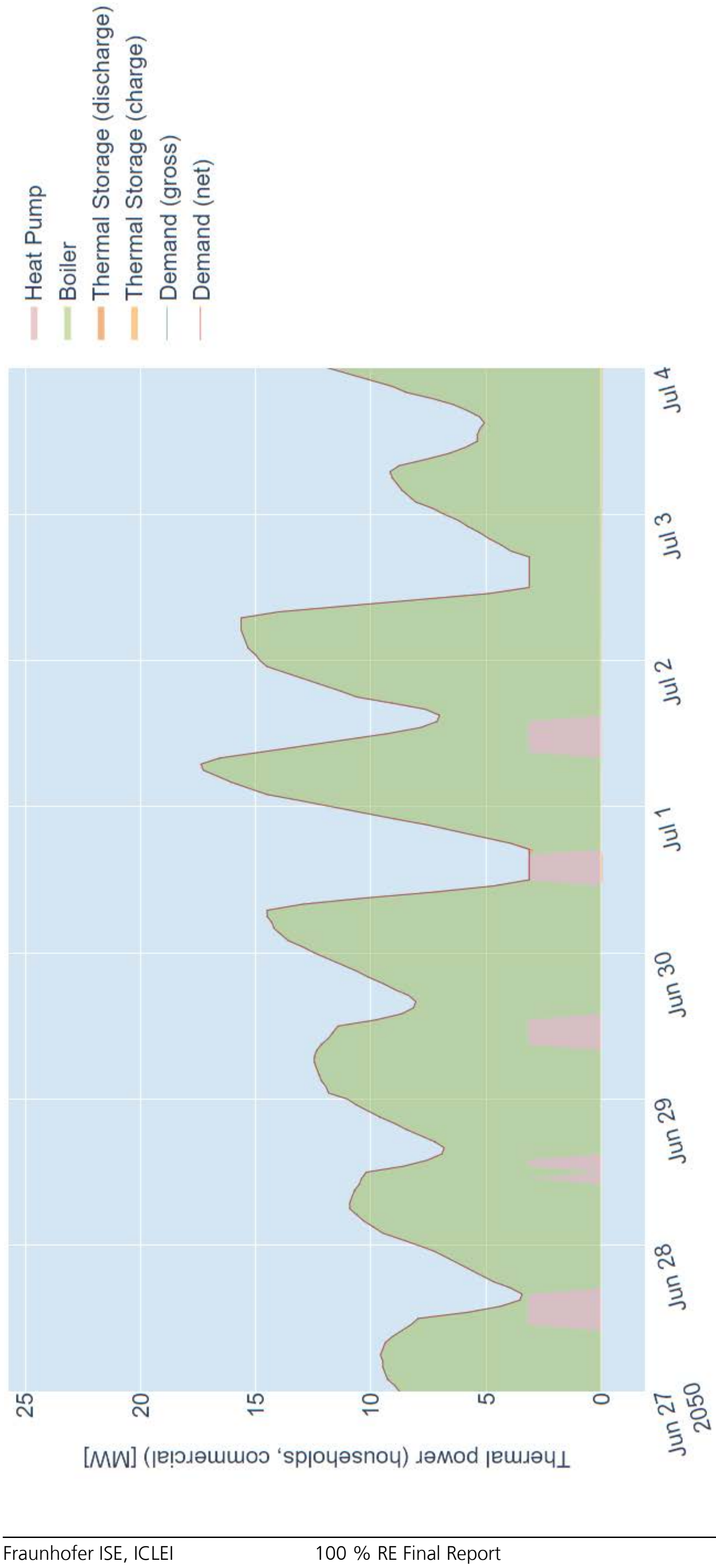
Leading scenario: One week in December, electricity supply and demand



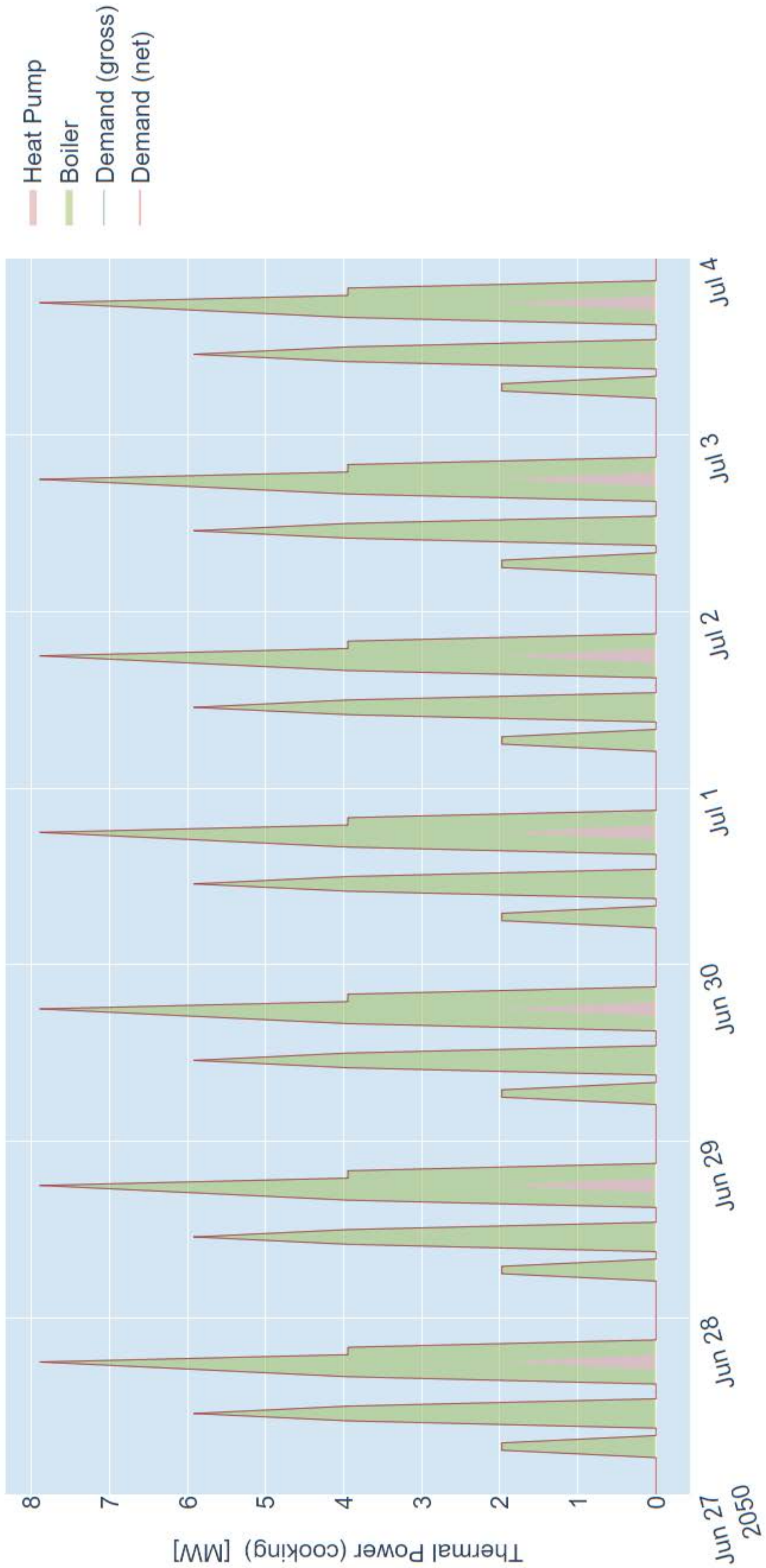
Leading scenario: one week in June: heating supply and demand in industry sector



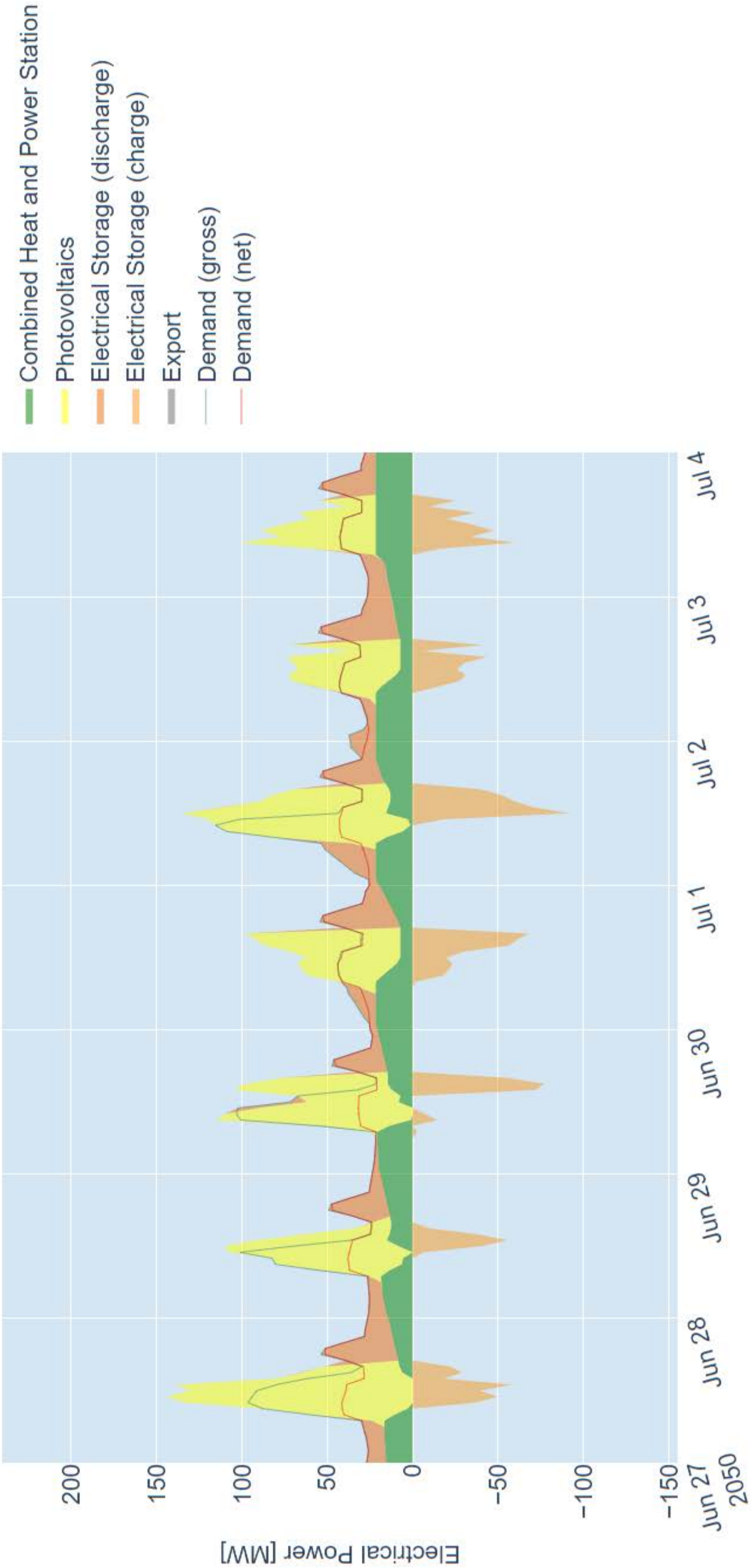
Leading scenario: one week in June: heating supply and demand in residential and commercial sector



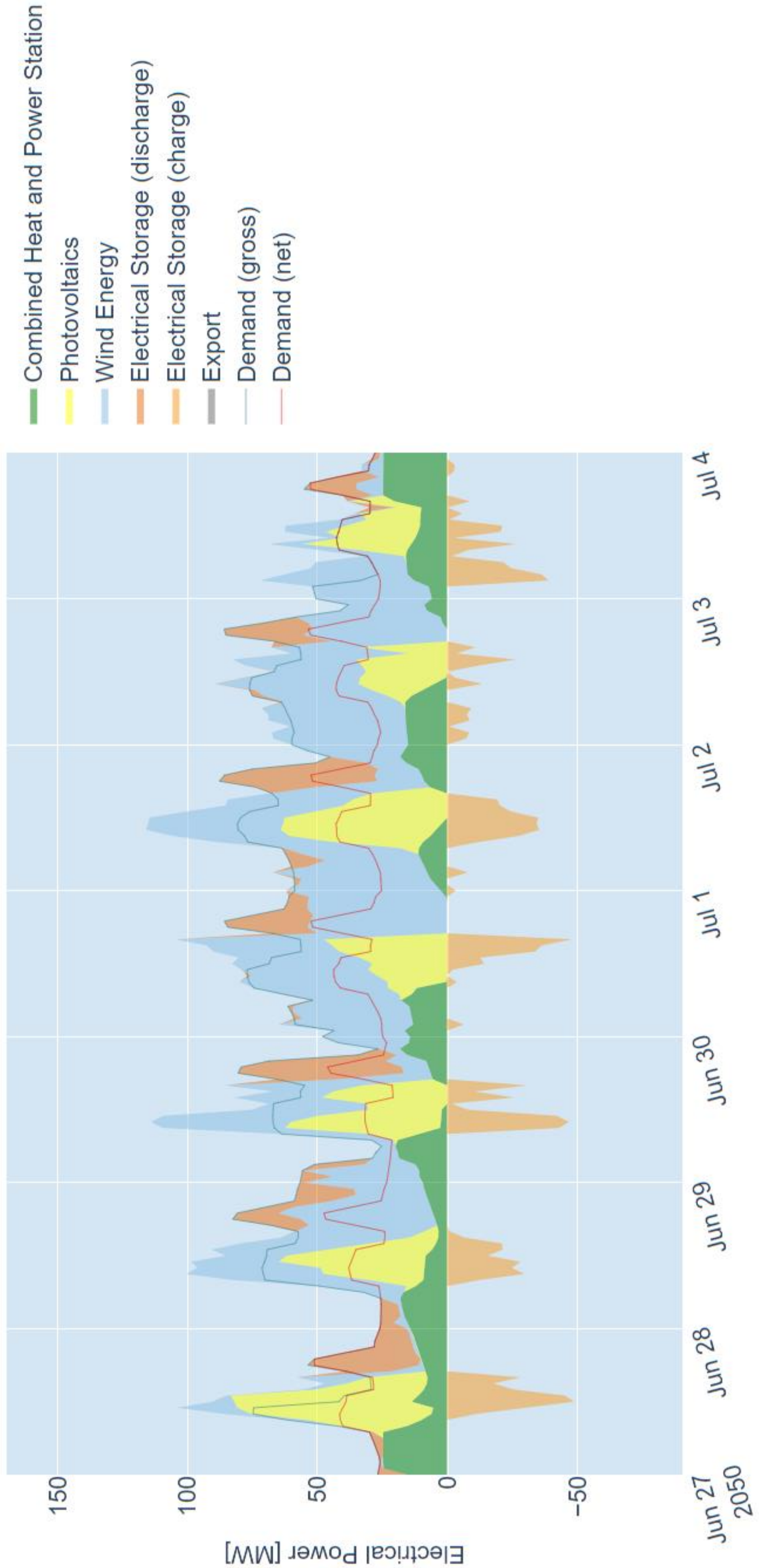
Leading scenario: one week in June: Energy supply and demand for cooking



No wind power scenario: One week in June, electricity supply and demand



Least-costs scenario: One week in June, electricity supply and demand



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